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A hybrid virtual-physical design methodology to enable the democratisation of design for FDM

A hybrid virtual-physical design methodology to enable the democratisation of design for FDM

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Abstract

New manufacturing methods such as Filament Deposition Modelling (FDM) have the potential to radically change the way in which we produce and consume everyday goods. They democratise manufacturing by enabling users to make functional, useful products. This is achieved without loss of capability and, when compared with traditional mass manufacturing methods, with reduced environmental impact and significantly lower manufacturing costs.

Despite these proven benefits, increased proliferation of these manufacturing technologies is prohibited by a lack of appropriate design tools for everyday users. Correspondingly, there is a need to democratise design for such users.

Existing design approaches principally constitute traditional CAD based methods and design repositories. The former offers high design freedoms but high requisite skills, and the latter the reverse with neither approach accommodating the huge design space afforded by FDM.

It is proposed that this could be addressed by using generative design approaches to augment the existing capabilities of design repositories. Correspondingly, this thesis presents an innovative generative design methodology that can be integrated within existing design platforms to greatly expand their capabilities and, in the process, provide design democratisation. It combines a knowledge base of manufacturing parameters, metaheuristic search algorithms and a fusion of activities from virtual and physical design processes – permitting quick iteration and simulation in the virtual space combined with testing and real-life performance validation in the physical.

The methodology is instantiated in the design of three load bearing components and when compared to a CAD based approach it is shown to provide a two thirds reduction in the quantity and difficulty of design steps that a user needs to undertake.

The work presented in the thesis represents a significant step towards the widespread uptake of technologies such as FDM as it enables the design and manufacture of parts with reliable mechanical properties. Further work would involve the extension of the method to other design tasks, and also its implementation within an existing design repository such as Thingiverse where its use can be monitored and evaluated.

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Author's Declaration

"I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author."

SIGNED:... DATE:..............

Publications

Journals

1. M. Goudswaard, B. Hicks, and A. Nassehi, ***"Towards a generalised capability profile for FDM to enable the democratisation of design,"*** Int. J. Agil. Syst. Manag., 2019 - Accepted, pending publication

Conference Papers

1. M. Goudswaard, A. Nassehi, and B. Hicks, ***"Towards the democratisation of design : the implementation of metaheuristic search strategies to enable the auto-assignment of manufacturing parameters for FDM,"*** in Proceedings of the International Conference on Flexible Automation and Intelligent Manufacturing, 2019,.
2. M. Goudswaard, H. Forbes, L. Kent, C. Snider, and B. Hicks, ***"Different approaches to democratise design - are they equal?,"*** in Proceedings of the International Conference on Engineering Design, ICED 2019, 2019.
3. M. Goudswaard, B. Hicks, and A. Nassehi, ***"Democratising the design of 3D printed functional components through a hybrid virtual-physical design methodology,"*** Procedia CIRP, vol. 78, pp. 394–399, 2018.
4. M. Goudswaard, B. Hicks, and A. Nassehi, "***Towards the democratisation of design : exploration of variability in the process of filament deposition modelling in desktop additive manufacture,"*** Proc. Conf. Transdisciplnary Eng., 2018.
5. M. Goudswaard, B. Hicks, J. Gopsill, and A. Nassehi, ***"Democratisation of design for functional objects manufactured by fused deposition modelling (FDM): lessons from the design of three everyday artefacts,"*** ICED 2017 Conf. Proc., vol. 5, no. August, pp. 219–228, 2017.
6. M. Goudswaard, B. Hicks, A. Nassehi, and D. Mathias, ***"Realisation of self-replicating production resources through tight coupling of manufacturing technologies,"*** in Proceedings of the International Conference on Engineering Design, ICED, 2017, vol. 5, no. DS87-5.

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List of Abbreviations

3DP	Three Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacture
CAPP	Computer Aided Process Planning
CAx	Computer Aided X
CNC	Computer Numerical Control
CP	Capability Profile
DfAM	Design for Additive Manufacture
DoD	Democratisation of Design
DOE	Design of Experiments
EA	Evolutionary Algorithm
FBS	Function Behaviour Structure
FDM	Filament Deposition Modelling
GPN	Global Production Network
IBIS	Issue Based Information Systems
IDEF	Integration Definition
KBE	Knowledge Based Engineering
NN	Neural Network
PET	Polyethylene terephthalate
PLA	Polylactic Acid
PSO	Particle Swarm Optimisation
RQ	Research Question
SA	Simulated Annealing
STL	Stereolithography/Standard Tessellation Language
TA	Technical Ability
TU	Technical Understanding
UTS	Ultimate Tensile Strength

Glossary

3D Printing	An additive manufacturing process that builds objects by depositing material layer by layer
Democratisation of Design	The process of allowing more non-designers to become involved in the design process
Design Repository	An online library of CAD designs
Distributed Manufacturing	A decentralised manufacturing paradigm that enables small-scale local manufacturing
Functional Model	A model that represents an object's behaviour
G-Code	A widely-used numerical control programming language used to operate automated machine tools
Generative Design	An often computational design exploration process where possible permutations of a solution can be explored
Global Production Network	The nexus of interconnected functions, operations and transactions through which a specific product or service is produced, distributed and consumed
Parametric Design	A design paradigm where the relationships between elements are used to manipulate and inform the design of geometries and structures
Slicing	The process of converting a CAD model into a G-Code manufacturing instruction
Structural Model	A model that represents an object's geometric structure

Chapter 1

Introduction

The purpose of this chapter is to present background review of a number of areas in order to frame and posit the research question of the thesis. To achieve this, it explores the benefits afforded by additive manufacturing and how distributed manufacturing is an empowering paradigm that can address current global issues to do with poverty and inequality.

1.1 Additive manufacturing

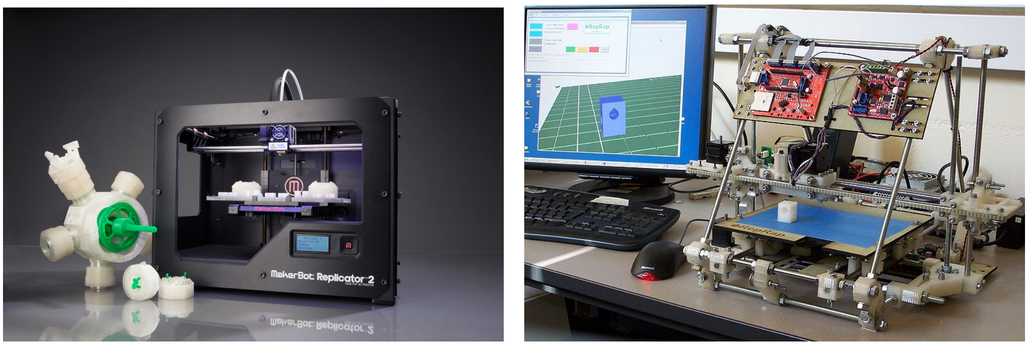
Additive Manufacturing (AM) or 3D printing are umbrella terms that refer to a number of manufacturing methods that produce parts additively through a 'process of joining materials to make objects from 3D model data, usually layer upon layer' [1]. They have many benefits over existing manufacturing methods. These include affording a range of design freedoms that permit the realisation of structures not possible by subtractive methods [2] and manufacturing cost reduction by eliminating the needs for tooling and molds [3]. In achieving this they also enable improved sustainability outcomes in business operational practices [4]. They also permit [5]:

- Designs to be optimised to reduce waste.
- Products to be made as lightweight as possible.
- Greater flexibility in the location of manufacturing.
- Products to be personalised to consumers.
- Consumers to make their own products.
- The manufacture of products with bespoke properties.

Because of these various benefits, additive manufacturing technologies are enablers of the manufacture of personalised products [4] [6] and have been part of the home fabrication movement that constitutes the local production of appliances, tools and replacement parts [7].

[1] S. H. Huang *et al. Additive manufacturing and its societal impact: A literature review.* (2013)
[2] M. Attaran. *The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing.* (2017)
[3] B. Berman. *3-D printing: The new industrial revolution.* (2012)
[4] J. Holmström *et al. Sustainability outcomes through direct digital manufacturing-based operational practices: A design theory approach.* (2018)
[5] Foresight. *The Future of Manufacturing: a new era of opportnunity and challenge for the UK.* (2015)
[4] J. Holmström *et al. Sustainability outcomes through direct digital manufacturing-based operational practices: A design theory approach.* (2018)
[6] M. Hannibal and G. Knight. *Additive manufacturing and the global factory: Disruptive technologies and the location of international business.* (2018)
[7] P. Holzmann *et al. Understanding the determinants of novel technology adoption among teachers: the case of 3D printing.* (2018)

Of a multitude of AM technologies, the technique that has gained the most traction in the consumer market is Filament Deposition Modelling (FDM) accounting for 69% of 3D printing technologies [8]. FDM can enable the affordable manufacture of parts in homes and communities and in doing this has been shown to have significant sustainability benefits, principally through the near elimination of supply chains [9]. This is of particular importance for rural areas in developing countries where up to 75% of the cost of goods arises from transportation [10]. A typical consumer level FDM machine that could be used for affordable home manufacturing is shown in Figure 1.1a.



(a) *A Hobbyist/Enthusiast level printer - Makerbot Replicator 2 from [11]*

(b) *The open-sourced RepRap Mendel 2 - from [12]*

Figure 1.1 *FDM 3D printers - Images licensed under creative commons*

A wide range of materials can be used as feedstock for FDM to manufacture a diverse range of parts. As the filament needs to be melted in order to be extruded, plastics are the main constituent parts of the filaments. The polymers that are most commonly used are plastics such as ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic acid). In addition to these, more exotic polymers such as polycarbonate, Nylon or PET (Polyethylene terephthalate) - the polymer used in plastic bottles - can also be used [13]. It is also possible to add other materials to achieve more diverse properties. These include [13]:

- **Polymer Matrix Composites** - with metal powder additives that can be conductive or higher strength.
- **Biocomposites** - include the addition of ceramics to make products biocompatible.
- **Fibre re-inforced composites** - incorporating glass and carbon fibre to provide high strength to weight properties.

[8] A. Holst. *Worldwide most used 3D printing technologies, as of July 2018.* 2018
[9] M. Gebler *et al. A global sustainability perspective on 3D printing technologies.* (2014)
[10] S. Fox. *Open prosperity: Breaking down financial and educational barriers to creating physical goods.* 2013
[13] N. Mohan *et al. A review on composite materials and process parameters optimisation for the fused deposition modelling process.* (2017)

In addition to this, it is also possible to combine properties by conducting multi-material prints [14]. This permits manufacture of parts with unique combinations of different materials in a single print. FDM is therefore able to manufacture a wide variety of products with diverse properties and is hence exceptionally versatile.

FDM was originally developed by Stratasys in 1988 [15]. Since the patent for the technology expired in 2009, prices for FDM machines have reduced by two orders of magnitude [16]. This is due largely to the development of the RepRap (Self-**Rep**licating **Rap**id Prototyper shown in Figure 1.1b) that provided [17] [18] free open source designs for FDM machines that could be freely reproduced and distributed. As of 2019 typical price points for 3D printers are as follows [19]:

- Budget/DIY printers $100-$300.
- Entry Level and Hobbyist printers $300-$1000.
- Enthusiast, professional and performance printers $1000-$10000.
- Industrial and business printers $10000+.

Printers can therefore be seen to be exceptionally affordable and with home use shown to be economically beneficial, saving the average US households thousands of dollars per year if consumer items were printed rather than purchased [20].

The utility and versatility of FDM has been demonstrated in a number of different projects. These include:

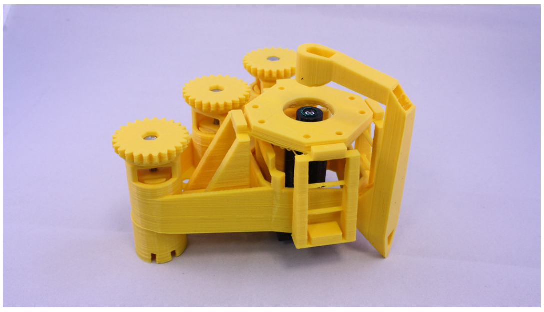
- **3D printed weather stations** - Through 3D printing low cost weather metrology was enabled for $200 where typical systems would cost into the tens of thousands [21].
- **Rural farming production** 63.2% cost reduction in manufacturing essential items for animal agriculture in rural areas [22].
- **Prosthetics** - 3D printing of prosthetics can be used to make bespoke

[14] D. Espalin *et al. Multi-material, multi-technology FDM: Exploring build process variations.* (2014)
[15] C. Kai Chua *et al. Rapid Prototyping: Principles and Applications, Volume 1.* (2003)
[16] G. Rundle. *A Revolution in the Making.* (2014)
[17] E. Sells *et al. RepRap : The Replicating Rapid Prototyper : Maximizing Customizability by Breeding the Means of Production.* (2007)
[18] R. Jones *et al. Reprap - The replicating rapid prototyper.* (2011)
[19] All 3DP. *How much does a 3D printer cost?* 2019
[20] B. T. Wittbrodt *et al. Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers.* (2013)
[21] H. Freitag. *United States: How 3D Printing Can Help Save Lives - ProQuest.* 2015
[22] S. Obydenkova *et al. Prospects of applying 3-D printing to economics of remote communities: Reindeer herder case.* (2018)

prosthetics for hundreds rather than thousands of dollars in days rather than months [23] [24]. A prosthetic hand manufactured via FDM is demonstrated in Figure 1.2a.

- **Disaster response** - FDM printers used in resource-deprived sites to produce essential medical supplies, replacement parts and more [25] [26].
- **3D printing medical equipment** - 3D life prints work in both developing and developed countries providing medical 3D printing services [27].
- **3D printed microscopes** - to enable low-cost medical diagnosis [28] [29]. One such example is shown in Figure 1.2b

(a) *3D Printed Prosthetic Hand. Image from public domain.*



(b) *Low-cost 3D Printed Microscope. Picture from [30] licensed under creative commons*

Figure 1.2 *3D printing use cases*

These examples demonstrate the utility of FDM and how it can be considered as a forerunner in the democratisation of manufacture by providing fabrication capability to the masses [31].

In addition to a broad spectrum of benefits and proven applications, future trends indicate a bright and expansive future for 3D printing. Results from Sculpteo's 2019 survey of 3D printing showed and increase from 38% to 51% in proportion of 3D printing applications that constitute final products with 70% of respondents reporting applications of 3D printing will grow in the next year [32]. Not only are 3D printing applications substantial but they are also growing.

[23] Enable Medellin. *About Us - Enable Medellin.* 2019
[24] Fabrilab. *About us - fabrilab.* 2019
[25] Field Ready. *About us - Field Ready.* 2019
[26] A Dara Dotz. *An ingenious solution for aid in disaster zones.* 2018
[27] 3D LifePrints UK Ltd. *3D life prints - about us.* 2018
[28] J. P. Sharkey *et al. A one-piece 3D printed flexure translation stage for open-source microscopy.* (2016)
[29] T. O'Connor *et al. Structured illumination in compact and field-portable 3D-printed shearing digital holographic microscopy for resolution enhancement.* (2019)
[31] A. Robinson. *The Democratization of Manufacturing and The Roles of Its Citizens.* 2014
[32] Sculpteo. *The State of 3D Printing 2019 Edition.* (2019)

Continued proliferation of 3D printing technologies can bring production to the masses; empowering individuals to make things themselves, in their own homes and communities. This is a desirable paradigm for the benefits afforded by 3D printing. More importantly, however, it enables us to address some stark and substantial issues associated with our current means of production and consumption. To consider this, we first need to explore our current manufacturing paradigm and its issues.

1.2 How we make things now

Current means of production and consumption are principally characterised by Global Production Networks (GPNs). These see the process of design, manufacture and distribution of items spanning the globe in order to achieve production at the lowest possible cost. GPNs involve 'all sorts of complicated systems in manufacturing, assembly and disposal; labour conditions and environmental standards; the geopolitics of resource extraction and supply chains; and the logics and motivations of consumer marketing, branding and corporate profit making' [33]. Despite their complexity, benefits of GPNs are felt at their front end by consumers and companies alike, with cheap consumer goods and high profits respectively.

As for the the drawbacks - these are experienced at the back-end of GPNs and largely in less developed countries. GPNs are characterised by regime-driven factories [33]. They depend on the international dimensions of austerity to remain unequal so that they continue to be profitable [34] [35]. They exclude property ownership, and with their dire track record for boosting living standards in developing countries [34], actually exacerbate poverty [33].

Why is the maintenance and exacerbation of poverty necessary? Due to their global nature, GPNs consist of long and complex valaue chains in which mistakes can occur at any point [36]. As a result, their cost effectiveness is driven by [37]:

- Cuts in product longevity and quality.
- Poor labour conditions in regions where production happens.
- Low wages for workers.

[33] T. Birtchnell and W. Hoyle. *3D Printing for Development in the Global South.* (2014)
[34] A. Sumner and R. Mallett. *The Future of Foreign Aid: Development Cooperation and the New Geography of Global Poverty.* (2013)
[35] S. George. *How the Other Half Dies: The real reason for world Hunger.* (1986)
[36] H Bapuji. *Not Just China: The Rise of Recalls in the Age of Global Business.* (2007)
[37] G. Slade. *Made to Break: Technology and Obsolescence in America.* (2006)

- Damaging environmental practices.

To summarise, the way in which we produce and consume requires inequality and poverty to function and remain profitable. GPNs, therefore, cannot provide for people in less developed countries as they depend upon people being excluded from property ownership and to experience material poverty in order to function. Changing the manner in which we make things could therefore have a massive impact in dealing with global poverty and inequality.

What does 3D printing have to do with this? Low-cost 3D printing technologies can enable anybody anywhere to manufacture what they need. By providing manufacturing capacity for a few hundred dollars, communities can take the reins of their own development. What's more, as materials like PET are suitable feedstock, waste plastics can be re-cycled into 3D printer filament - waste can be turned into a valuable resource. Centring a manufacturing paradigm around these could provide a solution. What would such an alternative manufacturing paradigm look like?

1.3 Distributed manufacturing as an alternative

Distributed manufacturing is an alternative paradigm that could help to remedy the issues associated with GPNs. It is enabled by digital manufacturing technologies such as 3D printing. It represents a growing democratisation and decentralisation of manufacturing [38]. It is characterised by a shift from large centralised manufacturing centres (characteristic of GPNs) to a shared collection of diversified and distributed manufacturing resources [39]. 'These small, flexible and scalable geographically distributed manufacturing units are capable of exhibiting the characteristics desired of modern operating systems' implying a 'move away from long supply chains, economies of scale and centralisation tendencies towards a network paradigm' [38]. This paradigm shift is depicted in Figure 1.3 which illustrates the change from globe-spanning separation of design, manufacture and consumption to a paradigm allowing their localised unification.

Distributed manufacturing not only signifies a move away from traditional manufacturing in terms of both scale and location, but also a blurring of the conventional boundaries between consumers and producers [40] leading to the emer-

[38] J. S. Srai *et al.* *Distributed manufacturing: scope, challenges and opportunities.* (2016)
[39] D. Wu *et al.* *Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation.* (2015)
[40] C. Kohtala. *Addressing sustainability in research on distributed production: An integrated literature review.* (2015)

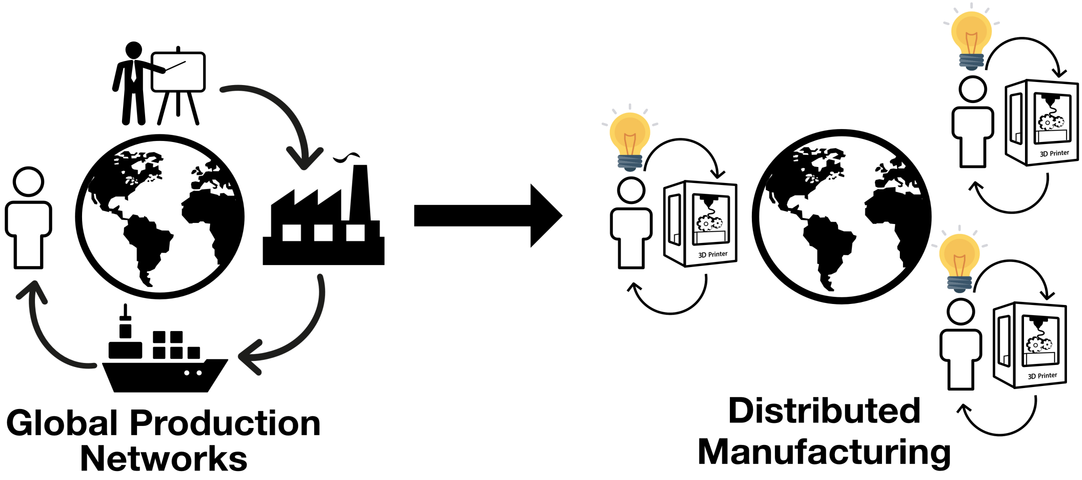


Figure 1.3 *3D printing can enable a paradigm shift in manufacturing from Global Production Networks to Distributed Manufacturing. Traditional boundaries between producers and consumers are blurred*

gence of 'prosumers' [41] - consumers empowered to provide input into production and innovate themselves.

There are two principle necessary requirements that would need to be met in order to enable the implementation of a distributed manufacturing paradigm. First, access to the internet is necessary. This is to enable access to information related to designs and operation of printers. Second, a reliable supply of electricity is necessary in order to enable prolonged use of manufacturing technologies. Because of this, the implementation of distributed manufacturing paradigms is not suitable to countries without suitable pre-requisite infrastructure. In addition to these general infrastructure requirements, others specific to users also need to be considered. These will be addressed in Chapter 4.

This provision for self innovation is empowering and represents a significant benefit of a distributed manufacturing paradigm underpinned by 3D printing particularly in the context of developing countries. The following section explores the importance of empowerment in greater detail.

1.4 Empowering benefits

As has already been explored in Section 1.1, 3D printing affords a number of benefits over traditional manufacturing methods. Whilst it could positively change the manner of production and consumption in developed countries, more crucially it could provide manufacturing capacity in developing countries where

[41] Y. Benkler. *Wealth Of Networks*. (2006)

their currently is none. It therefore has a very different driver, where 'consumption may simply mean survival' [42]. Provision of manufacturing capacity is empowering - this section elucidates why this is important.

3D printing powered distributed manufacturing does not only provide access to material goods. It is an empowering tool and as such the benefits it affords are much more widespread. Empowerment is the expansion of freedom of choice and action [43]. In the context of development it is 'the expansion of assets and capabilities of poor people to participate in; negotiate with; influence, control, and hold accountable, institutions that affect their lives' [44]. Assets are material things such as land, money and possessions. Capabilities are embodied within an individual or group of people and determine the way in which they can use their assets. They can be categorised as human, social or political. Whilst being a means to other objectives (such as providing access to essential items in the case of 3D printing) it is also a desirable good in itself as it is shown to 'enhance development effectiveness at the local level in terms of design, implementation and outcomes' [44]. Empowerment can therefore reduce the human degradation of powerlessness and release the energies of people to contribute to their societies [45].

In addition to providing access to a wide range of material items that would otherwise be unattainable, it also provides essential capacity to develop and implement solutions to local problems. In this way it enhances human capabilities by providing the ability to produce, social capabilities with the capacity to organise and political capabilities through permitting community development. In essence, it increases the provision of agency to people who otherwise would be unable to exact change on their own lives. By giving people the ability to design and produce locally you can contribute to these areas as they can design tailored products, repair artefacts and customise new bespoke products with the potential to use local resources by printing in timber or recycled plastic. It provides fundamental capability to design, redesign, reproduce, repair and re-use.

[42] C. Gibson *et al. Household Sustainability Challenges and Dilemmas in Everyday Life.* (2014)
[43] A. Sen. *Well-Being, Agency and Freedom: The Dewey Lectures 1984.* (1985)
[44] D. Narayan. *Empowerment and Poverty Reduction A source book.* (2002)
[45] D. Narayan *et al. Voices of the poor: Crying out for change.* (2000)

1.5 Inhibitors to uptake of 3D printing

Clear benefits of FDM, 3D printing and distributed manufacturing have been identified as contributing remedies to the significant global challenges associated with GPNs. This has been evidenced with a wide array of examples where they have been successfully implemented. Whilst some headway is being made towards their proliferation, there exist a number of barriers to their increased uptake. These are as follows and can be categorised as issues related to design (**D**), the manufacturing technology itself (**M**) or a combination of both (**D & M**):

- A PWC report elucidates this from the perspective of businesses. The top barriers to entry for 3D printing were identified as [46]:
  - Uncertainty in quality of the finished product **(D & M)**.
  - Lack of expertise to exploit the technology **(D)**.
  - Cost of 3D printers **(M)**.
- From the perspective of consumers the key barriers are [33]:
  - Cosmetic shortfalls and visual flaws of low-end plastic prints **(M)**.
  - Cost of materials without the benefit of bulk manufacturing **(M)**.
  - Unintuitive software and printer interfaces **(D)**.
  - Inability to compete with mass produced products backed by global marketing companies and global designers. **(D& M)**.
- Initial findings from studies undertaken to guide the UK's national strategy for additive manufacturing found the following to be the top 3 key issues [47]:
  - Understanding available materials and their properties **(M)**.
  - Lack of understanding in how to design for AM **(D)**.
  - Lack of people with skills to exploit AM and no educational framework to address this **(D)**.
- Sculpteo's 2019 survey exploring the state of 3D printing identified key areas inhibiting growth [32]:
  - Quality of parts and reliability of technology **(D & M)**.
  - High knowledge gap necessitating training and education **(D)**.
  - Easier to operate technologies **(D)**.

Whilst advances in manufacturing capability would invariably increase the util-

[46] R. McCutcheon *et al. 3D printing and the new shape of industrial manufacturing.* (2014)
[47] P. Dickens and T. Minshall. *UK Strategy for additive manufacture - Initial Findings.* 2015
[32] Sculpteo. *The State of 3D Printing 2019 Edition.* (2019)

ity and number of applications for 3D printing, given the wide range of existing applications (as explored in Section 1.1) it is evident that technologies available are already of a level to provide significant and useful manufacturing capability. In addition to this, printer manufacturers, researchers and maker movements drive significant innovation of the printers themselves. What therefore is the greatest inhibitor to increased uptake of 3D printing technologies is design itself. There is a pressing need for designers that understand the requirements and challenges of designing printable objects [7] or to re-frame the problem, a pressing need for design tools that better reflect the abilities of would-be designers. This is reflected in the UK's National Additive Manufacturing Strategy [48] that advocates the undertaking of research and development 'to address gaps in knowledge on design for AM, including the development/use of appropriate software and the integration of additive manufacturing design and production'.

Enabling people to design for themselves is also exceptionally important with respect to the benefits afforded by distributed manufacturing. If people are to be empowered by providing manufacturing capacity, it is essential that they are able to innovate and develop things that fit their needs. Design needs democratisation or, in other words, to undergo 'the act of making something accessible to everyone' [49]. This is the underpinning motive of the thesis and permits the formation of the research aim:

Aim

To create a design methodology to enable the democratisation of design for FDM.

Having explored the motivation behind the thesis aim, the following chapter provides a literature review to identify how this can be achieved and existing work in this area.

To address this research question, the thesis is structures as follows Table 1.1:

1.6 Chapter Summary

This introductory chapter has presented background and justification for the thesis aim which is to develop a methodology than can democratise design for 3D printing

The introduction has shown the various benefits afforded by 3D printing tech-

[48] P. Smith and J. Maier. *National Strategy 2018 - 25.* (2017)
[49] The Oxford English Dictionary. *Democratisation - definition.* 2018

nologies and, that of these, FDM is the manufacturing technique with highest adoption. Problems with our current methods of production and consumption have been identified and a paradigm of distributed manufacturing underpinned by FDM is proposed as a potential remedy. Benefits of this paradigm include the provision of material goods where they would otherwise be un-available, elimination of supply chains and, crucially, the empowerment of people to innovate and generate solutions to problems locally.

Inhibitors to increased proliferation of FDM technologies are explored and issues surrounding design are found to be a large contributing issue. This problem identification permits the formation of the research aim - to develop and implement a design methodology that can democratise design for FDM 3D printing.

Table 1.1 *Thesis Structure*

Chapter 2: Literature Review
The Introduction has framed the need to democratise design. Following this, the literature review explores in greater detail the definition of the research need and questions, and identification of avenues for achieving design democratisation.
Chapter 3: Research Framework
The research framework consolidates the findings from the Introduction and Literature Review into the research questions. It also assesses various research methodologies that could be used to address the research questions. One of these is subsequently chosen as the research approach of the thesis.
Chapter 4: Characterising the FDM Design Process
In order to democratise design for FDM, it is first necessary to understand where the difficulty in the design process lies. This chapter characterises the FDM design process to elicit the requirements of design democratisation from the perspective of a prospective user (would-be designer).
Chapter 5: Characterising the FDM Manufacturing Process
In addition to identifying difficulty in the design process, it is also necessary to develop an understanding of the capabilities of the manufacturing process. This chapter contains a literature review concerning existing FDM process knowledge and details material testing to identify impacts of additional parameters not currently covered in literature.
Chapter 6: Design Methodology Overview
Having identified the requirements for design democratisation from the perspectives of the user and manufacturing capability a design methodology able to democratise design can be proposed. This chapter presents an overall system architecture of the methodology, contextualises it with respect to existing design frameworks and demonstrates its function from the perspective of the user to show that design is democratised through its use.
Chapter 7: Verification
This chapter details the first implementation of the design methodology. This permits the verification of the suitability of the tools used to do this and also define an appropriate method of navigating the solution space.
Chapter 8: FDM Capability Profiling
The function of the design methodology is underpinned by a capability profile of the FDM process. This chapter details material testing undertaken to form a capability profile and validates its functionality.
Chapter 9: Validation
In this chapter, use cases of the design methodology are used to instantiate it and fully demonstrate and validate its functionality. Their selection, creation and design outcomes are presented. Based on the design outcomes of the use cases, the methodology is validated with respect to its ability to democratise design for FDM.
Chapter 10: Discussion & Further Work
The discussion assesses the generalisability of the methodology and further work, which includes the next steps that need to be taken in order to progress and further the proposed methodology.
Chapter 11: Conclusion
The conclusion reviews the work undertaken in the thesis and assesses how and where the research questions and subsequently thesis aim have been achieved.

Chapter 2

Literature Review

The Introduction has presented FDM 3D printing as a technology that can underpin a paradigm shift in the way in which we produce and consume goods. Whilst its numerous benefits are identified, a key inhibitor to its increased proliferation is identified as difficulties associated with design. Subsequently the research aim of the thesis is presented as developing and implementing a design methodology that can democratise design for FDM 3D printing. Given this aim, the literature review chapter has the following objectives:

1. To clarify terminology in the research question, particularly design for FDM - what does this mean and what does it consist of?
2. To identify research areas that need to be considered in developing a solution.
3. To identify existing work in the area of design democratisation.
4. To identify approaches where democratisation of design (or similar) has already been attempted and/or achieved.

The outcomes of the literature review are used to inform the research questions and objectives that will direct the remainder of the thesis.

The structure of the literature review is as follows. First an overview of design with particular attention to the engineering design process is given. This provides a definition and contextualisation of design and allows clarification of the thesis aim.

Second, a review of democratisation is provided covering design and broader areas of manufacturing and technology. Similarly, this provides clarification of the thesis aim with respect to democratisation, allowing a definition of democratisation and identification of existing work in the area.

Third, design for FDM is reviewed. Necessary processes to design and manufacture a part via FDM are identified and existing commercial, open-source and state-of-the-art design tools are presented. The affordances of these design tools are subsequently appraised. Correspondingly a combination of these design approaches is presented as a possible means of democratising design. It is upon this proposed combination that the research questions in the thesis are then placed.

2.1 Design

Design is 'the conception and realisation of new things' [50] and is not constrained only in the field of engineering. Everyone designs who devises courses of action

[50] N. Cross. *Designerly ways of knowing.* (1982)

aimed at changing existing situations into preferred ones. Whilst natural sciences relate to how things are, design is concerned with how things ought to be, through building artefacts or courses of action to attain goals. It is this principal mark that distinguishes the professions from the sciences. As well as engineering, schools of architecture, law and business (for example) are concerned with the process of design [51].

Whilst design specialisms have different approaches and ways of working, the Design Council's Double Diamond model describes commonalities of the creative approaches [52]. It recognises that in creative processes a number of possible ideas are created before being refined down to the best idea. Divergent thinking followed by convergent thinking. The Double Diamond process recognises that this happens twice. The first time to confirm the problem definition and the second time to create the solution. The four phases of the Double Diamond Design model are depicted in Figure 2.1 and are defined as follows:

1. **Discover** - the start of a project, collect information and gather insights to permit problem definition.
2. **Define** - make sense of the information and develop a creative brief that frames the fundamental design challenge
3. **Develop** - development phase where solutions or concepts are created and iterated.
4. **Delivery** - the finalisation, production and launch of the resulting project.

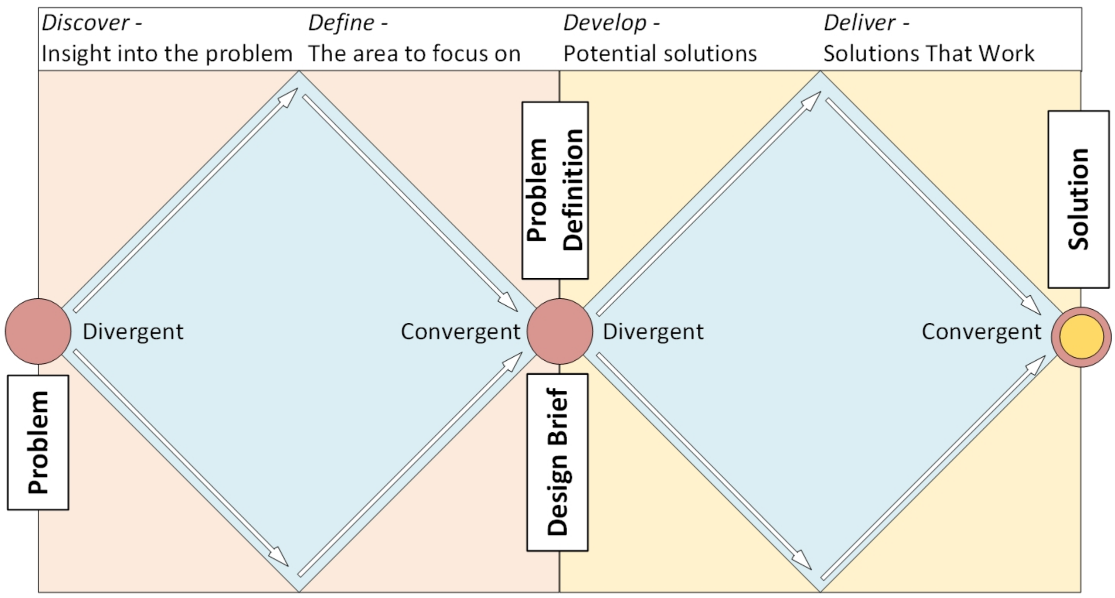


Figure 2.1 *The Double Diamond Design Model (From [52], re-illustrated)*

[51] H. A. Simon. *The Science of Design : Creating the Artificial Published by.* (1988)
[52] The Design Council. *The Design Process: What is the Double Diamond?* 2019

The Double Diamond Model by no means accounts for the details and particularities of the design process, but it does provide a good starting point to begin to understand its fundamental elements.

A subset of design is engineering design. The thesis aim refers to the democratisation of design for FDM and in this sense it relates most to engineering design. This sub-discipline will therefore be reviewed in more detail.

2.2 The Engineering Design Process

Engineering design constitutes 'activities that actually generate and develop a product from a need, product idea or technology' [53]. A number of strategic approaches exist for defining the design process. These encourage a problem focussed, yet creative approach that is compatible with other disciplines.

The engineering design process is formalised in order to promote best practice and allow it to be taught and learnt [54]. The design process can be considered as either descriptive or prescriptive. Descriptive design processes describe actions taken by designers. Prescriptive processes on the other hand prescribe a course of action that a designer should follow. The following sections will cover a number of descriptive and prescriptive design approaches.

There are many different ways of breaking down a design task into its separate phases. Pahl and Beitz separate the design process into four principle categories; clarification of task, conceptual design, embodiment design and detail design [54]. VDI 2221 [55] is a standard for the design process which is the same as Pahl and Beitz but omits the clarification of task. French separates the process into problem analysis, conceptual design, embodiment of schemes and detailing. This framework focuses principally on the conceptual phases. Cross categorises the process as exploration, generation, evaluation and communication [56]. Similarities can be observed in the way in which the design process is segmented. It is also noteworthy that each category has both divergent and convergent activities, as demonstrated in the double diamond model. Whilst there exist a number of taxonomies for the design process, for the remainder of the thesis Pahl and Beitz's design framework will be used to permit categorisation and identification of design activities.

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[53] L. T. Blessing and A. Chakrabarti. *DRM, a design research methodology.* (2009)
[54] G. Pahl *et al.* *Engineering design: A systematic approach.* (2007)
[55] VDI-Fachbereich Produktentwicklung und Mechatronik. *Systematic approach to the development and design of technical systems and products.* 1993
[56] N. Cross. *Engineering Design Methods: Strategies for Product Design, 4th Edition.* (2008)

2.2.1 Pahl & Beitz

Having briefly reviewed a number of models of the engineering design process, the Pahl & Beitz framework will be explored in greater detail. Within this framework the design process is broken down into four phases by the focus of activity that is taking place. These are:

- **Clarification of task** - Clarification of the task is about breaking down the design problem and clearly understanding what it is that needs to be solved. The key output from this phase is a requirements specification which clearly states what a proposed design solution must be capable of.
- **Concept Stage** – The concept phase involves the formulation, evaluation and selection of concept variants. Concept generation could be aided by literature, natural systems, existing technical systems or solutions to analogous problems. There are many systematic methods to find and evaluate appropriate design solutions.
- **Embodiment Stage** – Having decided upon a final concept, the embodiment stage involves the determination of overall layout and preliminary form for the design. Several embodiment designs can be needed before a final one is selected. Search and selection of optimum design layouts is necessary in order to find the best one. At this stage, things like manufacturing methods and materials must be considered.
- **Detail Stage** – With the design layouts finalised, the detail design phase involves the generation of final instructions for the technical product that detail the layout, form, dimensions and surface properties of all individual components. This for example could be in the form of 2D drawings or 3D models depending on the manufacturing method.
- **Upgrade and Improve** - Although not a 'formal' stage of the design process itself, it is indicated as a concurrent activity alongside the aforementioned design activities. This can be seen in Figure 2.2. It is important as it permits refinement in all stages of the design process from lessons learned, generally in downstream activities.

These phases of design tasks can subsequently be broken down further to form a systematic prescriptive model of the design process. This is shown in Figure 2.2 and defines the various activities that are involved in the design process. In addition to defining types of design activities, Pahl and Beitz also classify types of design. These are shown in Table 4.1 and demonstrate most importantly that only around a quarter of design tasks undertaken constitute original design. These will be used to elucidate the types of design tasks that people typically undertake with 3D printing and the mentioned activities will be used to classify the parts of the design process that need to be addressed in order to achieve design democratisation.

Table 2.1 *Design Mode Definitions - from [54]*

Type of Design	Description	Proportion of design
Original Design	Elaborating and original solution principle for a system	25%
Adaptive Design	Adapting a new system to a changed task	55%
Variant Design	Varying the size or arrangement of certain aspects of a system whilst the solution principle remains the same	20%

2.2.2 The FBS framework

An alternative descriptive method is the Functional Behaviour Structure (FBS) framework [57]. Rather than dividing the design process temporally, it splits design into interactions between three classes of variables; function (what an object is for), behaviour (what an object does) and structure (what the object is). Connections between these are made through experience. A designer ascribes function to behaviour and describes behaviour from structure [58]. The FBS process is shown in Figure 6.7. The depicted processes are defined as follows [58]:

- **Formulation** (process 1) design requirements in function are transformed into expected behaviour.
- **Synthesis** (process 2) expected behaviour is transformed into a solution structure.
- **Analysis** (process 3) actual behaviour derived from solution structure.
- **Evaluation** (process 4) comparison of actual and expected behaviour.
- **Documentation** (process 5) design description produced for manufacture of product.
- **Reformulation type 1** (process 6) design state amended in terms of structure if actual behaviour is unsatisfactory.
- **Reformulation type 2** (process 7) design state amended in terms of behaviour if actual behaviour is unsatisfactory.
- **Reformulation type 3** (process 8) design state amended in terms of function if actual behaviour is unsatisfactory.

[57] J. S. Gero. *Design Prototypes: A Knowledge-Based Schema for Design.* (1990)
[58] J. S. Gero and U. Kannengiesser. *The situated function-behaviour-structure framework.* (2004)

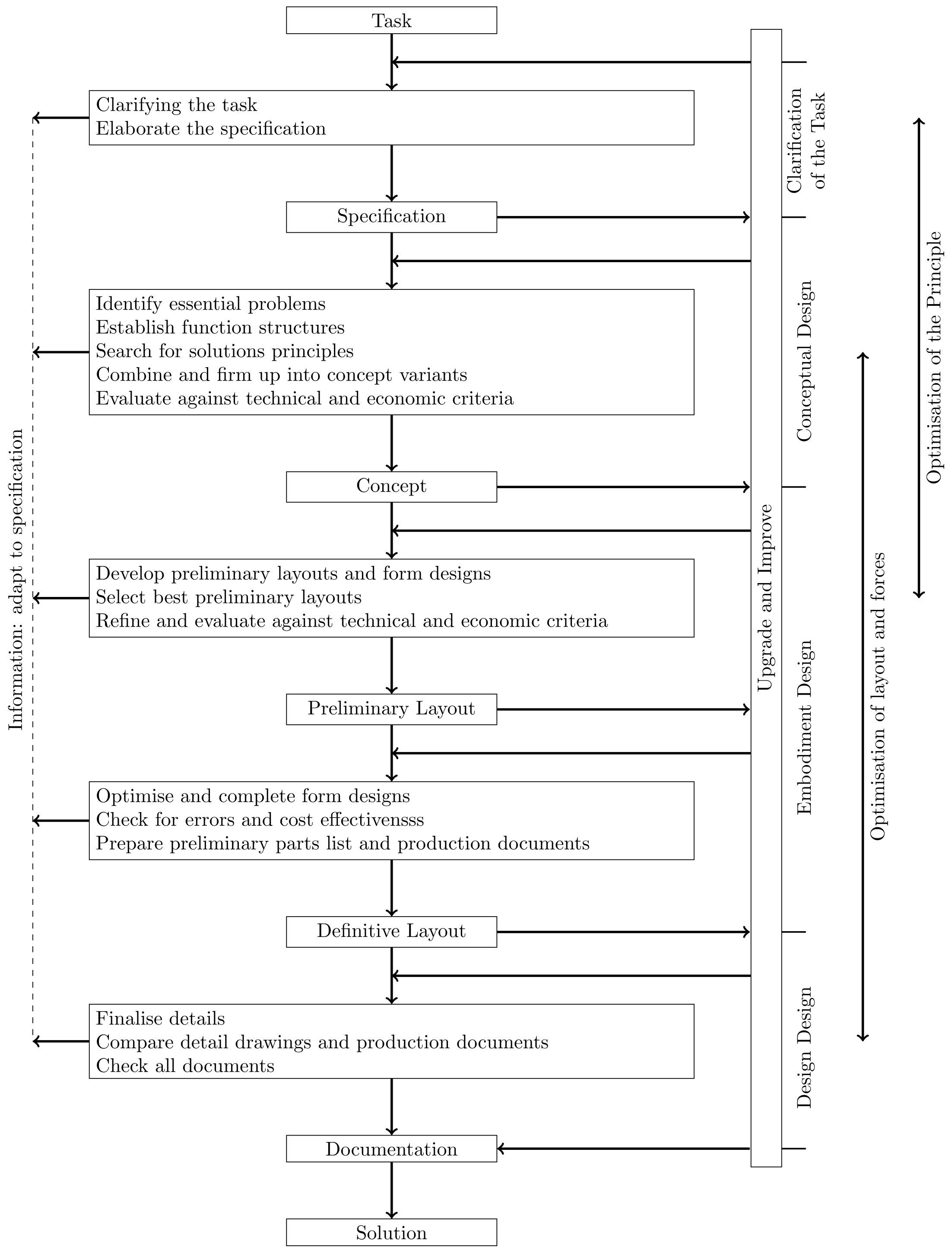

Figure 2.2 *Pahl and Beitz Systematic Design Process Model (From [54], re-illustrated)*

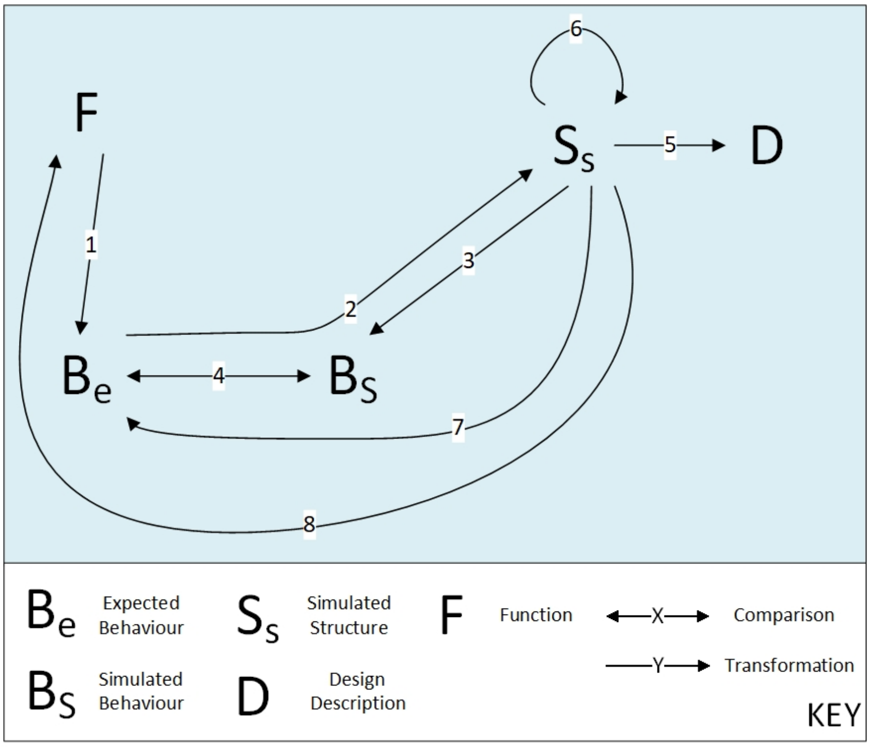

Figure 2.3 *FBS framework (From [58], re-illustrated)*

Where the FBS framework differs from other design models is that it paints a picture of a non-static world of design. The reformulation processes indicate a shift during design towards an un-expected direction.

2.2.3 *Selected models*

For the remainder of the thesis two design models will be principally used to situate the design methodology that will be developed to enable the democratisation of design. The Pahl and Beitz framework will be used for chronological situation and FBS to define and associate necessary design representations.

2.2.4 *Improving the design process*

Developing a design methodology to enable the democratisation of design could be classed as a means of improving the design process. Work exists in this area as success in product development is intrinsically linked to the success of the product itself. The driving factors in this are to reduce development cost, decrease time to market and increase product quality [59]. To achieve this, a number of approaches have been researched and include developing new design pro-

[59] D. G. Ullman. *The Mechanical Design Process Fourth Edition*. (2010)

cesses and methodologies [60], encouraging creativity [61] and the creation of novel method of representing designs and prototypes [62]. The democratisation of design, in decreasing barriers to entry to design functional products, could potentially be achieved in part or full by virtue of any of these.

2.2.4.1 Up-skilling, de-skilling & re-skilling

As a sub-set of impoving the design process - it is necessary to present the concepts of up-skilling, de-skilling & re-skilling. Up-skilling is about increasing the abilities of an individual so they can undertake a given task. De-skilling on the other hand is about decreasing the requisite complexity of the task so a less skilled individual is able to carry it out. The need to do this can be motivated by a systematic shortage of skilled labour [63] Additionally, there is the concept of 're-skilling'. This is where through automation of a task a user is able to focus and develop skills in other areas [64]. These distinctions will be used to identify the purpose of design tools that will be examined shortly.

2.3 The Democratisation of Design, Manufacture & Technology

The aim of this thesis is to develop and implement a design methodology that can democratise design for FDM 3D printing. The process of democratisation has been broadly defined as the act of making something available to everyone. In order to devise a methodology that can democratise design it is first necessary to carry out a review of literature concerning the democratisation of design and technology in general. This will allow:

- The formation of a more robust definition of democratisation with respect to design and related fields.
- The identification of parallel or similar trends.
- Additional justification of the potential benefits of democratisation.

[60] B. Camburn *et al. Design prototyping methods: state of the art in strategies, techniques, and guidelines.* (2017)
[61] B. Onarheim. *Balancing Constraints and the Sweet Spot as Coming Topics for Creativity Research.* (2016)
[62] A. K. Das. *CAD and rapid prototyping as an alternative of conventional design studio.* (2004)
[63] J. H. Bishop Carter, Shani. *The Deskilling vs. Upskilling Debate: The Role of BLS Projections. Working Paper # 90-14.* (1990)
[64] E. Orellana. *Deskilling, up-skilling or reskilling? Effects of automation in information systems context.* (2015)

2.3.1 The democratisation of design and related research areas

The democratisation of design is defined as the process of allowing 'more non-designers to become involved in idea generation, development and production of products, services or processes' [65]. In its most general sense the democratisation of design is desirable as diversity of thought enabled by public involvement is linked to improved ability to innovate [66] and enables the creation of better products [67]. Design democratsiation can be related to a number of different research areas which will now be explored.

Parallels can be drawn with open, distributed and collaborative design (AKA co-design) [68]. Open source design stems from software design and refers to 'the free revelation of source code' [69]. Open design is an expansion of this and provides a framework for sharing design information stemming from hardware as well as physical objects [70]. Open source design is therefore about allowing anybody with an appropriate set of skills to evolve the design of or innovate an artefact. The thesis aim to democratise design for FDM differs to these identified areas as it is about allowing as many end users as possible to innovate and design artefacts for themselves by lowering the skill level required to do it.

Participatory design is an approach to design that actively involves all stakeholders [71] [72]. Open innovation describes a system where innovation is not only performed internally within a firm, but cooperatively with other external actors [73]. This is similar to customer co-creation which is defined as an active, creative, and social process, based on collaboration between producers and customers [74]. It is an active collaborative process between producers and users [75].

Whilst all the above involve end user input and share similarities with the democrati-

[65] K. Fleischmann. *The Democratisation of Design and Design Learning: How do we Educate the Next-Generation Designer.* (2015)
[66] A. Hewlett *et al. How Diversity Can Drive Innovation.* (2013)
[67] L. Huston and N. Sakkab. *Connect and Develop: Inside Procter & Gamble's New Model for Innovation.* (2006)
[68] M. Koch and I. Y. Tumer. *Towards open design: The emergent face of engineering.* (2009)
[69] D. Harhoff *et al. Profiting from voluntary information spillovers: How users benefit by freely revealing their innovations.* (2003)
[70] R Vallance *et al. Open design of manufacturing equipment.* (2001)
[71] Wikipedia. *Participatory design.* 2019
[72] Participate in Design. *What is participatory design?* 2019
[73] R. Reichwald and F. Piller. *Interaktive Wertschöpfung -Open Innovation, Individualisierung und neue Formen der Arbeitsteilung.* (2009)
[74] F. Piller *et al. From Social Media to Social Product Development: The Impact of Social Media on Co-Creation of Innovation.* (2012)
[75] D. Schaefer. *Product Development in the Socio-sphere.* (2014)

sation of design, they do not necessarily constitute the end user designing for themselves as this is still carried out by expert designers, albeit with the end-user's requirements and needs incorporated. Additionally, these areas involve a separation of producers and consumers, with the producer generally being a business. This differs from the thesis aim, as enabling the democratisation of design is about empowering people to design for themselves.

2.3.2 Democratisation of Manufacture

Intertwined with design democratisation is the democratisation of manufacture. As already explored in the Introductory chapter, it is underpinned by a a suite of digital manufacturing technologies of which 3D printing is one of them (as discussed in the Introductory Chapter). The democratisation of manufacture is about bringing production to the masses and empowering individuals to make things themselves, in their own homes and communities [31].

A number of movements can be considered to come under the umbrella of the democratisation of manufacture. The first is the Digital Fabrication revolution. This is more conceptual and describes the general movement to home and community based manufacture underpinned by digital manufacturing technologies [76]. An exponent of this movement are Fab Labs (Fabrication Laboratories) that have rapidly spread across the globe over the last decade provide community based manufacturing capacity. As of 2019 there were 1,600 worldwide in over 100 countries [77].

The Wikihouse is another such movement [78] there mission is 'to put the tools & knowledge to design, manufacture and assemble beautiful, low-cost, low-carbon buildings into the hands of every citizen, community and business.' They freely provide designs to for open source, eco-friendly houses that are affordable to build.

2.3.3 Democratisation of Technology

The democratisation of design and manufacture have been defined according to the outcomes of projects with democratisation as their aims but have not allowed a full definition of what it actually means to democratise these areas. It

[31] A. Robinson. *The Democratization of Manufacturing and The Roles of Its Citizens.* 2014
[76] N. Gershenfeld. *How to Make Almost Anything: The Digital Fabrication Revolution.* (2012)
[77] Fab Labs Connect. *1,600 Fab Labs Worldwide.* (2019)
[78] Wiki House Foundation. *The WikiHouse Foundation.* 2017

is crucial to form a more robust definition so we can ascertain whether or not it has been achieved.

Both the Democratisation of Design and Manufacture can be classified as subsections of the Democratisation of Technology. The general aim of this is to increase the autonomy of local communities by devolving as much authority to them as possible. It is argued this can be achieved through public involvement in technological design and that this will favour advances that enlarge opportunities for people to participate in their futures over alternatives that enhance the operational autonomy of technical personnel [79] [80].

The Democratisation of Technology is a broad research area largely outside of the realms of engineering. It is useful to review as it allows a set of democratic design criteria to be explored which can then be used to define whether the thesis aim adheres to these. To do this, first a theory of technology to underpin these must be presented.

2.3.3.1 Theories of technology

Theories of technology can be represented in a table with two axes corresponding to whether technology is considered to be autonomous or humanly controlled, and whether it is neutral or value-laden - that is whether the ends (or aims) of a certain technology can be separated from the means (or methods). These theories of technology are shown in Figure 2.4.

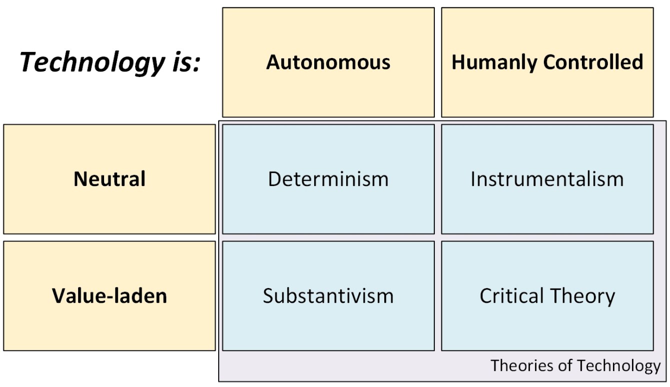

Figure 2.4 *Varieties of theories of technology (From [80], re-illustrated)*

Whilst beyond the scope of this literature review to cover these in detail, it is necessary to state which theory of technology will be adopted for this research in order to define how this shapes a definition and conditions of design democratisation.

[79] R. Sclove. *Democracy and Technology.* (1995)
[80] A. Feenberg. *Questioning Technology.* (1999)

The theory of technology used in this thesis is one of critical theory which holds that technology is both humanly controlled and value laden. It is not simply a neutral way to serve an end as the technological systems and artefacts created both embody social values and have social consequences and, as such, shape our lives in many ways. An artefact's content is influenced by social elements [81] meaning that content is not merely external to technology, but actually penetrates its rationality [82].

Critical theory of technology leads to technological polypotency in that artefacts have both focal function (intended purpose) and non-focal functions, effects and meanings [79]. Because of this, they can have significant political, social and economic consequences.

This is contrary to the most commonly held view of technology - instrumentalism - that it is humanly controlled and neutral. This is important as over the century it has shaped our responses to essential questions about socio-technical systems. They have been entirely expressed in an instrumental language of efficiency and productivity with little concern for the social impact these systems have on people or society [83]. Since the 19th century rapid technical advance has been sought at the expense of workers, communities and users of technology [82]. The end results of this could be considered to be GPNs as explained in the Introduction to this thesis, whilst their aim is create products at the lowest possible cost, their social effects are far broader in their necessitating and exacerbating poverty - they promote and reproduce continuity in power structures [84].

These systems are also not autonomous - they are humanly controlled and as such the technological paradigms we inhabit are chosen, created and their social consequences are of our own making. In this way technological intervention can be considered to be cyclical - we shape technology and then technology shapes us.

[81] T. J. Pinch and W. E. Bijker. *The Social Construction of Facts and Artifacts: or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other.* (1987)
[79] R. Sclove. *Democracy and Technology.* (1995)
[83] L. Winner. *Do Artefacts Have Politics?* (1986)
[82] A. Feenberg. *A Critical Theory of Technology.* (2017)
[84] M. M. Haklay. *Neogeography and the delusion of democratisation.* (2013)

The important consequence of the chosen theory of technology with regard to the research in this thesis is that technologies themselves can promote democracy by directly influencing political, social and economic structures and this can be guided by technological interventions. This is put best by Sclove:

> *"If citizens ought to be empowered to participate in determining their society's basic structure, and technologies are an important species of social structure, it follows that technological design and practice should be democratised [79]."*

Having defined the theory of technology used in this thesis, we can now explore existing design criteria for democratic technology that are built upon critical theory.

2.3.3.2 Design criteria for democratic technology

Whilst general guidelines and theories regarding the democratisation of technology are presented, the question remains as to how they should be incorporated within products and systems. Sclove describes a list of nine design criteria for democratic technology which enables demonstration of how a manufacturing paradigm underpinned by FDM can be considered democratic. These are shown in Table 2.2 along with explanations as to how some are met.

A manufacturing paradigm around FDM has been shown to meet these design criteria. It follows that as design is a key barrier to further proliferation of this paradigm, and also a crucial input to any manufacturing process, that the democratisation of design also adheres to Sclove's Democratic design criteria.

2.3.4 Concluding remarks

The democratisation of design, manufacturing and technology in general have been explored. This has permitted the identification of related research areas, definition of democratisation, identification of democratic design criteria and demonstration that the democratisation of design adheres to these.

[79] R. Sclove. *Democracy and Technology.* (1995)

Table 2.2 *System of design criteria for democratic technologies from Sclove [79], with comments as to how they are met specifically by FDM.*

Toward Democratic Community

A. Seek a balance among communitarian / cooperative, individualised and trans-community technologies. Avoid technologies that establish authoritarian social relations.

- *The empowerment enabled by FDM prevents authoritarian relations.*

Toward Democratic Work

B. Seek a diverse array of flexibly schedulable, self-actualising technological practices. Avoid meaningless, debilitating, or otherwise autonomy-impairing technological practices.

Toward Democratic Practices

C. Avoid technologies that promote ideologically distorted or impoverished beliefs.

D. Seek technologies that can enable disadvantaged individuals and groups to participate fully in social, economic, and political life. Avoid technologies that support illegitimately hierarchical power relations between groups, organisations, or polities.

- *Allows individuals to become producers within communities who were formerly disadvantaged and unable to do so.*

To help secure democratic self-governance

E. Keep potentially adverse consequences (eg environmental or social harms) within the boundaries of local political jurisdictions.

- *FDM enables manufacturing and its consequences to be kept local - the harm caused is not off-shored and out of mind.*

F. Seek relative local economic self-reliance. Avoid technologies that promote dependency and loss of local autonomy.

- *The provision of manufacturing capacity makes people independent with agency to create products that fulfil their needs.*

G. Seek technologies (including an architecture of public space) compatible with globally aware, egalitarian political decentralisation and federation.

To help perpetuate democratic social structures

H. Seek ecological sustainability

- *Printed parts can be recycled and reused multiple times. Filament can be manufactured from recycled plastics or natural fibres.*

I. Seek 'local' technological flexibility and 'global' technological pluralism.

- *FDM exists as part of a suite of digital manufacturing technologies that can be adopted globally but tailored to local needs.*

2.4 Design for 3D printing

Design, Engineering Design and Democratisation have been explored so far in this chapter. This section will identify what constitutes the design process for 3D printing and also tools that exist within it.

The realisation of a functional part via a 3D printing technique such as FDM has four main stages. These are shown in Figure 2.5 for CAD based design generation, as process activities and are defined as Design for AM, Process planning for AM, Part build, and Part Validation. Of these, the first two are of most interest as they constitute the two areas in which design freedom can be found, and, as they constitute activities up-stream of manufacture, they represent all phases of the engineering design process.

'Design for AM' constitutes the generation of a 3D model of a required part. This defines a part's external geometry and consists of the phases of the engineering design process explored in Section 2.2.1. 'Process planning for AM' involves the assignment of manufacturing parameters and subsequent generation of a manufacturing tool path. These parameters define a part's internal structure. This is also considered as part of the detail design phase. Through combination of these two activities, a manufactured part's behaviour is fundamentally defined.

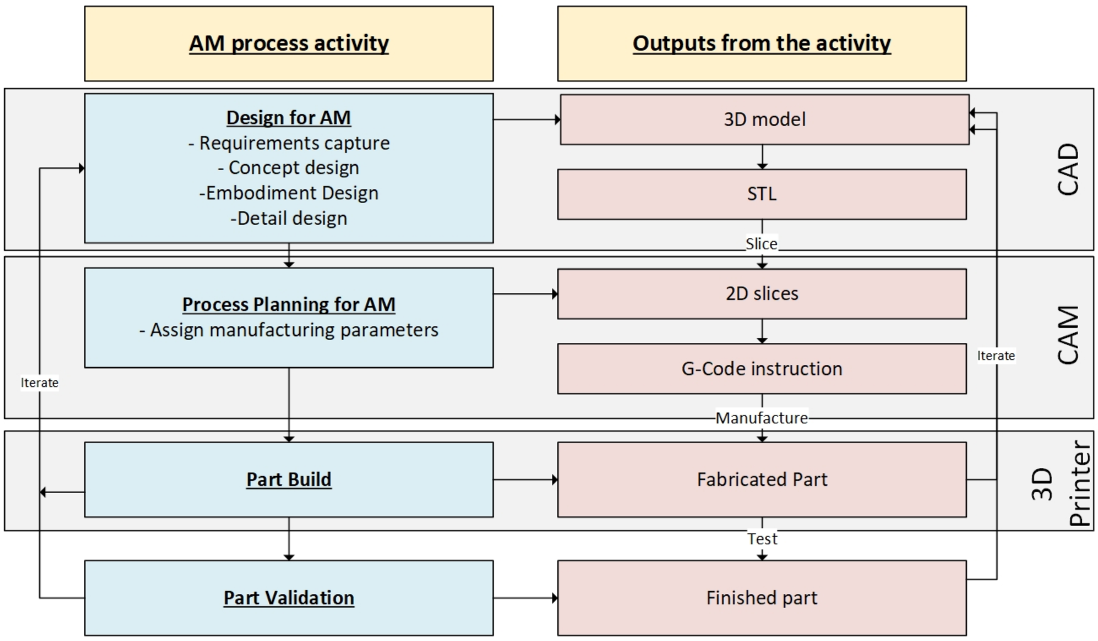

Figure 2.5 *Elements of AM fabrication process. Adapted from [85]*

Design for AM outputs models first in a CAD tractable format. These are often specific to the CAD software used. For slicing, this must be converted to a CAM tractable format of which the most common is the Stereolithography (STL). Once in this format geometric amendments to a model cannot be made.

An alternative to using CAD is to use a design repository. By using these a user can download one of many freely available designs already in an STL format. This results in greatly reduced steps in the design process, but also limits design flexibility. The corresponding AM process involving a repository is illustrated in Figure 2.6.

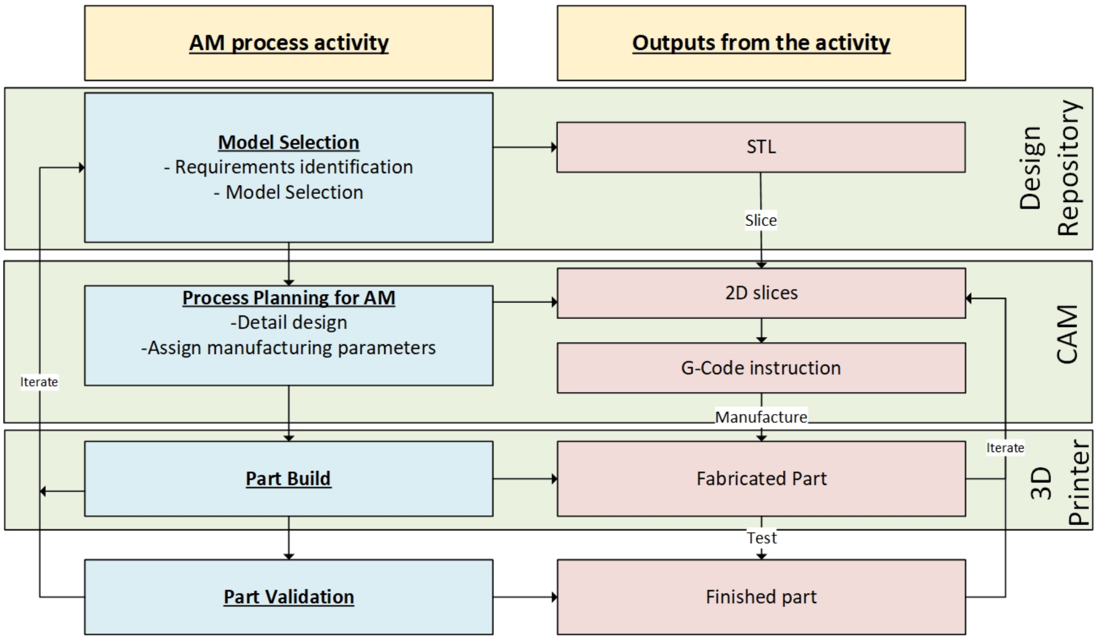

Figure 2.6 *Elements of AM fabrication process with use of design repository*

These various activities constituting the AM process will be explored in greater detail as they can be carried out in differed ways. As demonstrated,'Design for AM' can be carried out manually by a user with a variety of CAD tools or designs can be provided by a design platform requiring the user just to select an appropriate model. 'Process Planning', 'Part Build' and 'Part Validation' can either be carried out manually by a user (as shown above) or can also be outsourced to a design platform. To review these approaches, the following sections will consider CAD, CAM and Design Platforms for AM.

2.4.1 CAD tools

CAD tools permit users to create digital models. For the purpose of this review, they are separated into those that are commercially available or free to use.

2.4.1.1 Commercially available

Commercially available CAD packages include Autodesk Inventor £2,286 per year [86], Solidworks $1295 per year [87], Siemens' CAD offerings in the form of Solid Edge (for $230 per month) [88], Rhinoceros 3D [89] (for $850) and the more advanced NX [90] for upwards of $7000.

Whilst being powerful modelling tools they come with hefty price tags and their un-inuituive, complex interfaces yield steep learning curves for a user to become proficient in their use.

2.4.1.2 Free to use

Alternatives to commercial packages include those that are free to use or open source. TinkerCAD is a free offering from Autodesk [91]. Other alternatives include Trimble Sketch up, Free CAD, LibreCAD, 3DSlash, and BlocksCAD [92] [93].

As these are free to use, as one would expect, their capabilities are significantly lower than their commercial counterparts. They are limited with respect to the size of model they can open, and have reduced simulation capabilities when compared to their commercial counterparts. Paid for packages also offer more user support. In spite of efforts to reduce complexity for the user, free to use CAD packages still exhibit difficulties with respect to user interfaces providing a still significant barrier to entry.

2.4.1.3 Appraisal

Whilst CAD systems afford excellent design freedoms, they possess a number of drawbacks. Firstly, CAD software is generally speaking not intuitive [94] and requires time and skill to become proficient with. In addition to this, CAD tools are difficult to obtain and use and their input/output devices interrupt creativ-

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[86] Autodesk Inc. *Autodesk Inventor Overview.* 2019
[87] Dassault Systems Solidworks Corporation. *Solid Works 3D CAD.* 2019
[88] Siemens. *Solid Edge.* 2019
[89] Robert McNeel & Associates. *Rhinoceros.* 2019
[90] Siemens. *Siemens NX.* 2019
[91] Autodesk Inc. *TinkerCAD.* 2017
[92] M. von Ubel. *Best Free Online CAD Software Tools in 2019.* 2019
[93] Lifewire. *Top Free CAD Programs for 2019.* 2019
[94] R. Ibrahim and F. Pour Rahimian. *Comparison of CAD and manual sketching tools for teaching architectural design.* (2010)

ity [95]. It is also found that making design changes with CAD is difficult [96].

Although identified as difficult and unintuitive, it is unclear exactly what specifically within these CAD systems makes this the case.

When contextualised with respect to the Pahl & Beitz engineering design framework explored they represent a tool that corresponds to practically all phases of the design process. This represents a significant strength of CAD as they can usefully be use in concept generation, embodiment and detail phases.

2.4.2 CAM tools

Computer Aided Manufacturing (CAM) is the process of using software and computer controlled machinery to automate a manufacturing process. In the context of 3D printing this involves the conversion of a CAD model to a G-code manufacturing instruction. This represents the tool-path the 3D printer will follow in order to realise the requisite part. This is known as slicing (dividing a continuous model into discrete layers) and is carried out by slicing software. The input CAD model is combined with a set of manufacturing parameters (selected by the user) to create this.

A plethora of capable slicing software is available [97]. These include commercial offerings such as Autodesk's Netfabb and a wide range of free slicing packages that can be bespoke to 3D printer brands (such as Ultimaker's Cura) or open to be used with a variety of 3D printers.

The slicing process for 3D printing requires a user to select their manufacturing parameters which significantly impact the properties of a manufactured part.

The separation of the CAD and CAM processes is significant as it requires two stages to determine important parameters that come together in combination to define an object's behaviour. These are typically areas considered separately as Design and Manufacture respectively. To reap the benefits afforded by AM design freedoms, these areas need to be considered together. This is also identified by Thompson et al. who identify this also as an opportunity for FDM, stating that 3D printing will re-define the role of designer and manufacture by bringing them together [98].

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[95] Y. T. Shih *et al. Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modelling in design processes.* (2017)
[96] C. Ranscombe *et al. Designing with LEGO: exploring low fidelity visualization as a trigger for student behavior change toward idea fluency.* (2019)
[97] A. Locker. *Best 3D Slicer Software for 3D Printers in 2019 (Most are Free).* 2019
[98] M. K. Thompson *et al. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints.* (2016)

2.4.3 Design platforms for FDM

Design platforms are alternative means of acquiring digital models that one would wish to manufacture. Rather than the digital models being made by the user, they can be retrieved from design platforms which offer a range of services. A 2015 review paper by Rayna et al. categorised them as follows [99]:

- **Design Supply** - Designs (3D models of objects) created by the platform are offered (for free or for a fee) to customers. Examples include Trinckle's design marketplace [100].
- **Design Hosting** - Platform hosts third-party designs that are sold (marketplace) or offered free of charge (repository). Makerbot's Thingiverse is a widely used design repository [101] with a history of use, having reached over 340 million downloads and over 3 million uploaded artefacts in 2018 [102].
- **Design Customisation** - Designs (own or third-party) can be customised (e.g. shape, size, layout) by users.
- **Co-design service** - Assistance offered to consumers when designing a 3D object, generally by transforming two-dimensional sketches or pictures into a 3D object. Shapeways in a current example of this [103].
- **Design Crowdsourcing** - Users can crowdsource a design by posting a detailed project that is then developed further by the crowd.

These types of design platforms are shown in Figure 2.7.

[100] Trinckle. *Design Marketplace.* 2019
[101] MakerBot. *MakerBot Thingiverse.* 2019
[102] F. Leighton. *MakerBot Thingiverse Celebrates 10 Years of 3D Printed Things.* 2018
[103] Shapeways. *Shapeways.* 2019

A current review of platforms revealed a more convergent picture than the one painted by Rayna et al. in 2015. Whilst a number of platforms exist they either provide:

- Static models in design repositories (Such as Thingiverse [101]).
- Customisable models - largely in an aesthetic sense. (Such as Thingiverse's Customiser [104]).
- Co-design service in collaboration with an expert (such as Shapeways [103]).
- 3D print services (such as 3D Hubs [105]).

In the same way that separation exists between CAD and CAM in the 3D printing process, the same can be observed in design platforms. They either provide designs or they provide a manufacturing service. Platforms do not exist to merge the two - even though this identified as a key area for FDM development.

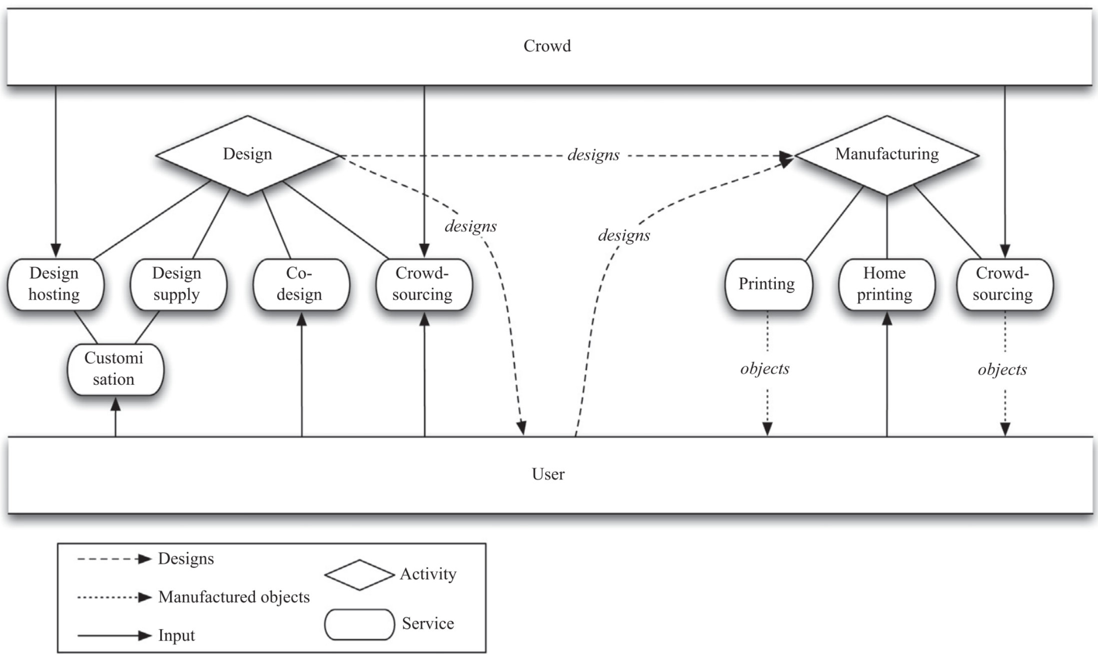


Figure 2.7 *Functions of online print platforms. Figure from [99]*

2.4.4 Implications

From this review of Design for FDM, a number of implications can be presented.

Whilst CAD provides design freedom and spans the entire design process, users are inhibited by high skill level necessary to realise products using these tools. On the other hand Design platforms provide designs freely but that do not provide flexibility. Neither provide assistance in selection of manufacturing parameters and as such, negate their importance at the design stage even though they

[105] 3D Hubs. *3D Hubs - About us.* 2019

are large contributors to the flexibility and versatility of 3D printing. The tailoring of designs to a user's individual manufacturing capability is also notably lacking in existing CAD tools and design platforms.

Design platforms do however provide a level of design democratisation and due to their widespread use, could provide a strong basis on which increased design democratisation could be enabled.

Another notable finding is the clear separation of CAD and CAM present in all design strategies for FDM. Platforms and print services all deal with one or the other but both are fundamental in defining the behaviour of functional parts they both need to be considered in a more holistic manner in order to exploit the affordancs of 3D printing.

2.5 State of the art in design

This literature review will now look at the state of the art in design. 3D printing specific design tools and platforms have been explored in depth, this section will look at more general trends and approaches in design.

2.5.1 *Assisted creation*

Assisted creation refers to a wide range of tools that exist to assist humans to perform "creative" tasks [106] and to help people to be "more creative more of the time" [107]. They constitute a wide variety of tools that enable creativity and can be classified into three generations:

1. **First generation assisted creation** - systems that mimic analogue tools with digital means. The creative process is fully human driven but computational tools provide some assistance.
2. **Second generation assisted creation system** 'In these humans and machines negotiate the creative process through tight action-feedback loops' [106]. Creative control is shared between user and computer with decisions made collaboratively with the system. Second generation systems are ubiquitous today, widely used examples being auto-correct and auto-tune. These lower the necessary skills to use these systems and enable people to be more creative more of the time without getting tied up in the minutiae detail.

[106] R. Pieters and S. Winiger. *On the Democratisation & Escalation of Creativity.* 2016
[107] B. Shneiderman. *Creating creativity: user interfaces for supporting innovation.* (2000)

3. **Third generation assisted creation systems** are systems that negotiate the creative process in fine-grained conversations, augment creative capabilities and accelerate the skill acquisition time, from novice to expert. In this way they not only carry out tasks on behalf of the user, they teach the user and help them become more proficient.

Existing CAD tools are largely first generation assisted creation systems as creative control remains fully in the hands of the user. The following sections will explore Generative design - a design method that can be classified as a second generation assisted creation tool.

2.5.2 Generative design

Generative design is a subset of assisted creation that is about designing not only the object but a process to generate the object [108]. These could be classified as simple parametric design tools which allow the user to manually manipulate parameters in the constrained design of an object with geometric rules defining the size of forms generated.

These can then be extended to generative approaches that create structures in response to functional requirements. There are a number of existing approaches that can do this that are commercially available and also others presented in academic literature.

2.5.3 Commercial Generative Design packages

Autodesk offer Generative design as part of their Fusion 360 package [109]. The software generates structures based upon user defined constraints. It does not de-skill the task, it up-skills. A user requires good understanding of the problem in order to define loads and constraints. As a consequence, a novice user would be unlikely to be able to design functioning structures.

In addition to these, the CAD packages listed in Section 2.4.1 offer their own similar generative design tools.

An alternative to these is Paramate which is a generative / parametric design service [110]. The design process for a given product is parametrised for clients to provide dynamic models that a customer can then use to instantiate to specific requirements. Through use of the tool 'design is democratised' [110].

[108] M. Hansmeyer. *Building Unimaginable Shapes*. 2012
[109] Autodesk Inc. *Generative Design*. 2019
[110] Trinckle. *Paramate*. 2019

2.5.4 Generative design for AM in academic literature

In addition to commercial generative design approaches, additional approaches can be found in academic literature which are more specific to 3D printing. These include:

- Methods for topological optimisation of additively manufactured parts [111].
- The creation of an interactive tool that generates 3D printed legs for walking robots based upon a desired motion profile [112].
- The amendment of internal and external properties of printed parts to allow them to balance. Essentially re-distributing mass to move CoM [113].
- Managing manufacturing parameters to optimise moment of intertia of a structure to increase spinning time of a spinning top [114].
- The generation of 3D printed model joints that can provide friction during operation in order to make a functioning prototype [115].
- The generation of custom 3DP infill based upon required load and specific load profiles [116].

These examples demonstrate how generative approaches are being used and developed already in design for 3D prinitng. Their limitations however are in the skill levels required to use the commercial tools, as the problem still needs to be bounded, and while academic applications are under development these are typically very specific in their goals and remit.

2.5.5 Knowledge Base Engineering

KBE is a generative approach that is non-specific to 3D printing. Its objective is to 'guide the designer who lacks experience' [117] or to free up a capable engineers' time from repetitive, routine tasks and focus on creation and innovation. It is recognised as an excellent technology for rapid design [118] and it is subsequently suggested that KBE is a suitable tool for performing routine design

[111] F. J. Silva *et al. A Novel Approach to Optimize the Design of Parts for Additive Manufacturing.* (2018)
[112] V. Megaro *et al. Interactive Design of 3D-Printable Robotic Creatures.* (2015)
[113] R. Prévost *et al. Make It Stand: Balancing Shapes for 3D Fabrication.* (2013)
[114] M. Bächer *et al. Spin-it: Optimizing Moment of Inertia for Spinnable Objects.* (2014)
[115] J. Calì *et al. 3D-printing of non-assembly, articulated models.* (2012)
[116] J. Gopsill and B. Hicks. *Deriving infill design of fused deposition modelled parts from predicted stress profiles.* (2016)
[117] E. J. Reddy *et al. Knowledge Based Engineering: Notion, Approaches and Future Trends.* (2015)
[118] S. Cooper *et al. Achieving Competitive Advantage Through Knowledge-Based Engineering A Best Practice Guide.* (2001)

tasks [117]. As such, it is reviewed here as its accolades suggest it may be appropriate for design democratisation.

Previous examples of KBEs include a system that selects standard parts for a mechanical system [119], Schemebuilder which supports the design of mechatronic systems through the conceptual through to embodiment stages of design [120] and more recently their application to successfully generate hull structures for ships [121]. KBE is used in an aerospace company to enhance knowledge sharing between design and test engineers to reduce the number of steps required to go between CAD and CAE [122]. In a similar context it is used to undertake parallel analysis of geometry, mass and manufacturing cost by iterating finite element and parametrised rotor models [123].

The similarities underpinning all these KBE implementations are that they have generally looked to reduce the engineer's time spent doing routine tasks so they can focus on more innovative elements of product development. These applications can subsequently be classed as up-skilling. Findings from KBE can be applied in the development of bespoke assisted creation tools.

2.5.6 Design for Additive Manufacturing (DFAM)

A further useful research area is Design for Additive Manufacturing. It is is defined as:

> *"A set of methods and tools that help designers take into account the specificities of AM(technological, geometrical, etc.) during the design stage [124]"*

These consist mostly of rules, methodologies and frameworks and can be broken down into two sub-categories. First 'DFAM in the strict sense' that covers the actual design stage. Second, 'DFAM in the broad sense' which includes additional processes such as parts selection and manufacturability analysis [125].

[119] B. J. Hicks and S. J. Culley. *An integrated modelling environment for the embodiment of mechanical systems.* (2002)
[120] R. H. Bracewell and J. E. E. Sharpe. *Functional descriptions used in computer support for qualitative scheme generation—"Schemebuilder".* (1996)
[121] J. J. Cui and D. Y. Wang. *Application of knowledge-based engineering in ship structural design and optimization.* (2013)
[122] A. Corallo *et al. Enhancing product development through knowledge-based engineering (KBE) A case study in the aerospace industry Angelo.* (2009)
[123] M. Sandberg *et al. A knowledge-based master model approach exemplified with jet engine structural design.* (2017)
[124] F. Laverne *et al. Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study.* (2015)
[125] M. Kumke *et al. Methods and tools for identifying and leveraging additive manufacturing design potentials.* (2018)

DfAM in the strict sense includes approaches concerning the actual design approach. These include guidelines and methodologies enabling AM design potentials or ensuring that AM design rules are adhered to. Examples of these in literature are typically the presentation of exemplar product designs where these are exploited. These include the topological optimisation of components to minimise weight [126] or the application of AM to make conformal cooling ducts [127]. Further examples include the experimental collection and subsequent implementation of design rules for various AM techniques by determining their respective limitations [128]. Other opportunistic methods identify the design freedoms afforded by AM and provide guidelines as to how these can be used. An example of this is the development of AM design feature databases [129].

DfAM in the broad sense includes up-stream, downstream and other DfAM related activities. Examples are the selection of an appropriate manufacturing process for a given design based upon accuracy of build speed [130]. It also includes processes that enable the selection of products that are suitable to be manufactured additively. For example, the identification of elements of a part that could be re-designed to be AM optimal [131].

Kumke et al. provide a more holistic DfAM framework that seeks to provide comprehensive design support in all phases of the design process[132]. Whilst the framework is only theoretical and no implementation is presented it provides a useful reference as to where in the VDI 2221 design process different AM considerations need to be taken into account. For example when iterating, to consider part consolidation, to assess manufacturing process feasibility in the concept phase and ensuring AM conformity in the detail and embodiment phases. In their DfAM framework, the authors combine embodiment and detail design phases as they note design processes typically see frequent iteration between these phases. This is noteworthy as it is similar to the need to combine CAD and CAM for AM identified in Section 2.4.4. Further work by Kumke et al. explores the interdependencies between AM design complexities and the benefits

[126] D. M. Watts and R. J. Hague. *Exploiting the design freedom of RM.* (2006)
[127] V. Petrovic *et al. Additive layered manufacturing: Sectors of industrial application shown through case studies.* (2011)
[128] G. A. Adam and D. Zimmer. *On design for additive manufacturing: Evaluating geometrical limitations.* (2015)
[129] M. Shajahan Bin *et al. Development of a design feature database to support design for additive manufacturing.* (2012)
[130] Y. Zhang *et al. A new decision support method for the selection of RP process: Knowledge value measuring.* (2014)
[131] C. Klahn *et al. Design strategies for the process of additive manufacturing.* (2015)
[132] M. Kumke *et al. A new methodological framework for design for additive manufacturing.* (2016)

that they afford products [125]. This links means and ends by connecting manufacturing capability and the potential requirements of products.

The general remit of DFAM is the leveraging of particularities of AM technologies for niche industrial or academic purposes. In this respect they are technology focussed and driven rather than identifying the needs and requirements of prospective users. This is subsequently identified as a need for current DFAM research; developments in academia will need to be transferred to industry and practice. [98]. DfAM as a research area provides useful references as to the design considerations for additive manufacture that would need to be incorporated in a methodology aiming to achieve the democratisation of design.

2.5.7 Summary

In summary, a number of powerful assisted creation tools have been identified that exist in the domain of 3D printing. KBE has also been identified as a non-AM specific assisted creation approach with many proven applications in engineering design. These typically correspond to later stages of design - typically from embodiment onwards as the design problem must be appropriately constrained in order to generate an appropriate solution.

Design for Additive Manufacture has been explored and provides a useful overview of design rules and recommendations that need to be taken into account at different stages of the engineering design process.

2.6 Research Gap

From the literature reviewed in the preceding sections, the findings can be consolidated to determine a research gap.

Design, Engineering design and Design democratisation were elaborated upon in order to better define the area of the thesis aim and permit assessment of existing design strategies for FDM.

CAD systems were reviewed and these were found to provide flexibility but little guidance and have high skill barriers to entry. The precise causes of the difficulty are also not well defined so it is unclear what exactly contributes to it. CAD systems are found to be appropriate for all phases of the design process.

[125] M. Kumke *et al. Methods and tools for identifying and leveraging additive manufacturing design potentials.* (2018)
[98] M. K. Thompson *et al. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints.* (2016)

As alternatives, design platforms including design repositories offer a wide range of designs that can often be freely downloaded by the user but these cannot be amended to a user's individual requirements or their manufacturing capability. As such, they offer designs limited in flexibility and are only suited to the detail phase of design.

In both 'Design it Yourself' CAD approaches and with design platforms there is a dichotomy between design and manufacturing (CAD & CAM) where in reality in the case of 3D printed parts, the two are inseparable as they both have huge impacts on part performance. There is a need to design in a manner than concomitantly considers both.

Generative design is proven in a wide variety of contexts to be an effective assisted creation tool - but its effective use still requires a bounding of the problem which is a highly skilled task in itself - requiring both knowledge of the design task and system or tool being used. Can new assisted creation or generative approaches be developed to be used as democratising aids as opposed to mechanisms for up-skilling? This is identified as a significant trend in 3D printing [32].

Given the suitability of KBE for routine design tasks, it is an appropriate means of developing an assisted creation system to democratise design.

Given these findings, and the context of this thesis, a possible means to democratise design would be to use generative design approaches to augment the capability of design repositories. The problems themselves are already bounded within the repositories. Therefore generative design tools could be effectively deployed to generate design solutions. In reaching a solution to this, it is necessary to take a more user focussed approach than has been taken in existing DfAM research whilst ensuring that the specificities of AM are incorporated in the appropriate areas of the design process.

2.7 Chapter summary

This literature review has explored areas of design, engineering design, the design process for 3D printing and assisted creation. This was carried out in order to clarify terminology in the research question and identify what specifically within design for FDM needs to be democratised and a potential solution for achieving this.

The findings from this chapter will be brought together to form three research questions which will frame the research to be carried out in this thesis. These

[32] Sculpteo. *The State of 3D Printing 2019 Edition.* (2019)

will be defined in the following Framework chapter.

Chapter 3

Research Framework

This chapter presents a research framework that will be followed for the remainder of the thesis. It specifies how the thesis aim will be achieved and develops three research questions.

3.1 Thesis Aim & Research Questions

The previous two chapters have provided a contextual basis for the aim of research undertaken in this thesis which is:

To create a design methodology to enable the democratisation of design for FDM

FDM printing is able to democratise design and provide valuable manufacturing capacity worldwide, but most notably in the global south where it is an empowering tool for development by providing access to currently unavailable essential items. Whilst the manufacturing capability exists, people are currently unable to design the objects they need. Design therefore needs to be democratised. However it is first necessary *to identify the requirements of a methodology that can enable the democratisation of design* or rather what currently inhibits a user designing for themselves.

Existing design methods for FDM have been explored and categorised as CAD approaches, which are found to be difficult to use, and design platforms which offer a plethora of freely downloadable designs but these are not specific to an individual users requirements. Generative design has been identified a useful method of assisting creation with a wide range of proven applications. It is subsequently posited that generative approaches could be used to augment the capabilities of existing design platforms. That is, *how can the functionality of design platforms be augmented with generative design to enable the democratisation of design?*

Answers to the questions above permit the development of a design methodology that can be used to democratise design. Once developed, it is crucial to understand if it is able to meet its intended goal of democratising design and how it achieves this. This is essential as it enables the validation of the research undertaken. Correspondingly, this raises the following question; *how is the democratisation of design enabled by incorporating a generative design approach into existing design platforms?*

It follows that in order to meet the aim of the this thesis, three research questions are developed:

- **RQ 1** - What are the requirements of the democratisation of design for FDM?
- **RQ 2** - How can generative design approaches be used to augment the existing capabilities of design platforms?
- **RQ 3** - How is design democratised by incorporating a generative design approach into existing design platforms?

This chapter presents the research methodology that will be followed in order to answer these questions.

3.2 Research Methodologies

A number of approaches exist to define an approach to design research. This section will give an overview and appraisal of three methods before defining the one that will be adhered to in this thesis.

The methodologies considered are based upon findings from the literature review. The review of Design for Additive Manufacture identified a lack of capturing user needs. This is due to the majority of research in this area focussing principally on the application and exploitation of AM capability. A means of addressing this is identified in literature as the incorporation of elements from other fields such as Interactive Design where creativity methods and knowledge engineering tools are integrated [125] [133]. As such, the research methodologies that are considered are from a variety of research fields and will involve the elucidating of user needs.

The research to be considered are Action Research, Design Research Methodology and a Design Research Approach.

3.2.1 Action research

Action research is defined by Stringer as [134]:

> *"A systematic approach to investigation that enables people to find effective solutions to problem they confront in their everyday lives"*

[125] M. Kumke *et al. Methods and tools for identifying and leveraging additive manufacturing design potentials.* (2018)
[133] J.-P. Nadeau and X. Fischer. *Research in Interactive Design (Vol. 3) - Virtual, Interactive and Integrated Product Design and Manufacturing for Industrial Innovation.* (2011)
[134] E. Stringer. *Action Research.* (2013)

An alternative definition is the 'the study of a social situation with a view to improving the quality of action within it' [135].

Action research is used by many researchers in the field of Engineering Design to address highly-contextually dependent problems. As such, whilst the output of this research can be profound in its specific context, the results produced can often have issues with respect to their generalisability [136].

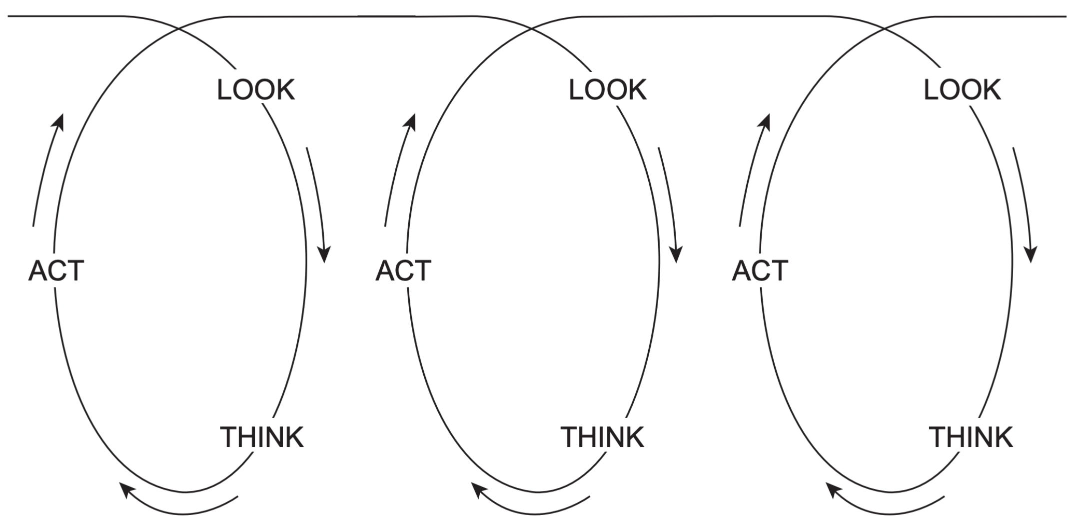


Figure 3.1 *Act, think, look cycles within action research from [134]*

The process of action research typlically consists of the actions of 'look, think, act', which are subsequently interated upon [137]. These cycles are demonstrated in Figure 3.1. In carrying out the research the researcher is directly involved. In trying to improve a teaching process for example, the researcher could be either a student (a participatory member) or a teacher (provider of a process) [138].

This methodology is widely used by social scientists to understand the social interactions of individuals in a given context. It is also popular in policy development, particularly where experience within the area are crucial and is built over many years such as medicine and foreign policy [139] [140]. It is also widely used

[135] J. Elliott. *Action research for educational change.* (1991)
[136] J Gopsill. "A Social Media Approach to Support Engineering Design Communication". 2014
[137] S. Kemmis *et al. The action research planner: Doing critical participatory action research.* (2014)
[138] R. G. Kane and C. Chimwayange. *Teacher action research and student voice: Making sense of learning in secondary school.* (2014)
[139] R. Flessner and S. Stuckey. *Politics and action research: An examination of one school's mandated action research program.* (2014)
[140] G. O'Sullivan *et al. Action research: Changing history for people living with dementia in New Zealand.* (2014)

in the improvement of student learning [141].

Whilst the application of this research methodology could provide profound insights into the democratisation of design for an individual item, as the results are likely to not be generalisable, the approach is unlikely to yield a design methodology that is able to democratise design on a wider scale.

3.2.2 Design Research Methodology

Blessing and Chakrabartis' Design Resesarch Methodology (DRM) [53] is a popular research methodology in design research.

Design research aims not only to understand the phenomenon of design, but also to apply this understanding to improve the current situation. This requires three things; first, a model or theory of what exists; second, a model or idea of what would be desired; and, finally a defined approach that can allow this to be realised. DRM was developed in order to combine two streams of design research that would typically approach either understanding of design or process improvement independently [53].

The DRM framework is presented in Figure 3.2 and includes four stages:

- Research Clarification.
- Descriptive Study I.
- Prescriptive Study.
- Descriptive Study II.

A researcher can carry out any one of these stages independently, however for the purpose of the research carried out in this thesis it is necessary to proceed through all of the prescribed stages. The refinement of the thesis aim and development of research questions represents the research clarification. Understanding the requirements for democratisation of design would constitute Descriptive Study I. The Prescriptive Study would entail the creation and instantiation of a design methodology that can meet the requirements identified. Descriptive Study II consists of a detailed analysis of the results enabling assessment of if and how the democratisation of design has been achieved.

3.2.3 A design research approach

To facilitate the research and development of appropriate means to support design the CAD Centre at the University of Strathclyde developed a design re-

[141] M. A. Nasrollahi. *A Closer Look At Using Stringer's Action Research Model in Improving Students'.* (2015)
[53] L. T. Blessing and A. Chakrabarti. *DRM, a design research methodology.* (2009)

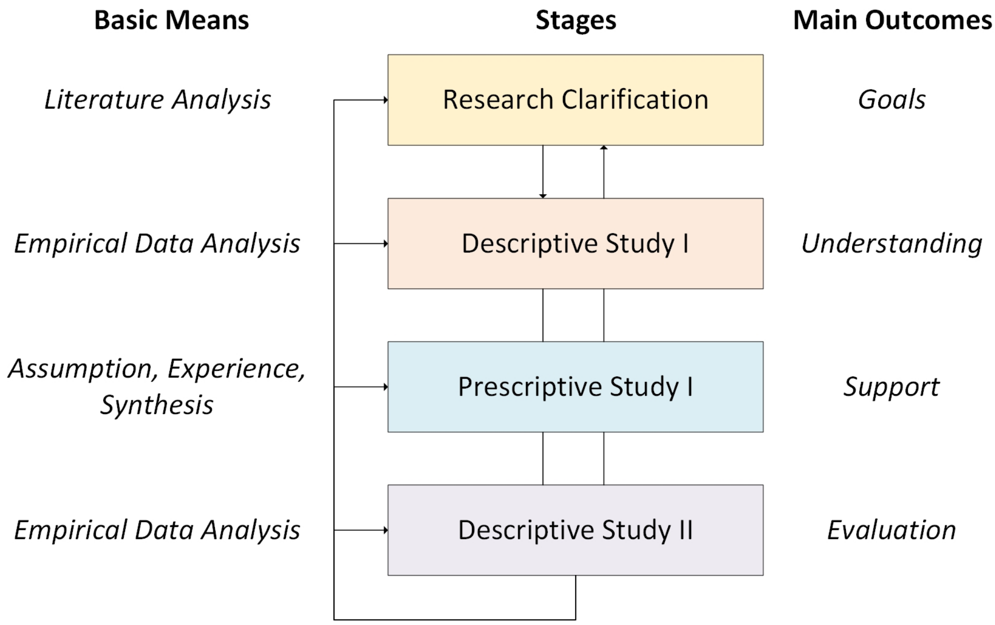


Figure 3.2 *Design research methodology adapted from [53]*

search approach that consists of the following phases [142]:

- **Research motivation / vision** - this reflects the overall objective and motivation for the research, including the long term goals of the team carrying out the research.
- **Needs analysis** - a needs analysis of design practice setting the basis and justification for carrying out the research.
- **Research framework** - a framework in which to carry out the research.
- **Research approach** - a template for carrying out the research, subject to alteration depending upon findings.
- **Validation and evaluation methods** - means of assessing the effectiveness and validity of the research results.

Within the methodology there is a focus on both validation and evaluation, with validation being whether the aims are met or not and evaluation a measurement of the level of impact. This is important as with the aim of achieving design democratisation it is crucial the extent to which it has been achieved is ascertained.

Whilst the methodology does provide value, its structure is very similar to that of Blessing and Chakrabarti's DRM and it is less widely used.

[142] A. Duffy and F. O'Donnell. *A design research approach.* (1999)

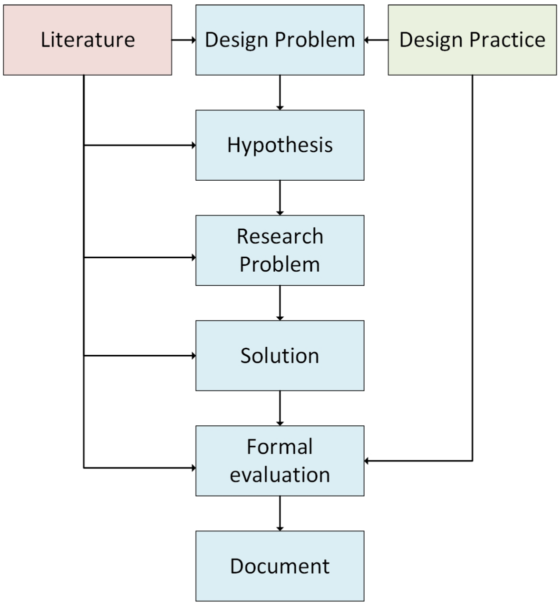


Figure 3.3 *A design research approach adapted from [142]*

3.3 Selected research approach

Blessing & Chakrabartis' Design Research Methodology will be the research methodology applied in this thesis. Table 11.1 demonstrates how the previously stated Research Questions correspond to the phases of DRM. This section explains how the research within this thesis aligns with the different phases of the selected design approach.

Research clarification has already been carried out in the Introduction and Literature Review chapters preceding this one. This consisted of exploration of the wider research area and more specifically design approaches for 3D printing. These have permitted the formation of a thesis aim and three clear research questions. Table 11.1 shows how these research questions align with the phases of the adopted DRM. These research methods will now be discussed.

The aim of RQ1 is to *elicit the requirements of the democratisation of design* and

Table 3.1 *DRM stages with their corresponding research questions*

DRM Stage	**Research Question**
Descriptive I	**RQ1** — *What are the requirements of the democratisation of design for FDM?*
Prescriptive I	**RQ2** — *How can generative design approaches be used to augment the existing capabilities of design platforms?*
Descriptive II	**RQ3** — *How is design democratised by incorporating a generative design approach into existing design platforms?*

constitutes the Descriptive I stage of the selected research framework. This consists of identification of the requirements of a prospective user (Chapter 4) and also formation of understanding of FDM manufacturing capability (Chapter 5). This will take the form of a further in-depth review of literature and user studies or testing in the event that reviewed literature is unable to paint a clear enough picture. Up on these, requirements of design democratisation can be found.

Based upon these requirements, the formation of Prescriptive Study I is possible. This corresponds to RQ2 that looks to explore *how generative desisgn approaches can be used to augment the existing capabilities of design platforms*. It is a proposed means to rectify an identified problem and in this thesis consists of the presentation (Chapters 6, 7 & 8) of a design methodology that can meet the identified requirements.

The Descriptive II stage of DRM permits the assessment of if and how the prescribed solution is able to meet its goal and given this, what its significance is. This has two parts. First, the validation of whether the developed tool is able to democratise design. This is carried out in the form of case studies which are used to assess how the design process has been changed through the use of the proposed methodology. This enables the determination of whether *individual instances* of design democratisation have been achieved and if so, how they do it. Second, an evaluation of the generalisability of the results alludes to whether *wider design democratisation* can be achieved through further use of the proposed methodology. It is identifies that the 'evaluation of design support is a complex, challenging task that requires creativity and careful preparation in order to obtain meaningful results' [143] and also that in the development of evaluation methods it is necessary to innovate and improvise in order to gain credible, defensible evidence [144]. As such, careful consideration will be given to the evaluation methods developed and employed.

3.4 Research Plan

This chapter has so far presented the three research questions, followed by a review of various research methodologies, the selection of DRM to frame the thesis and subsequently demonstrated how the research questions align to the different phases of the selected research methodology. This section will provide a breakdown of the chapters and activities within them, mapped chronologically to the proposed research questions. This provides the reader with a cartographic key to the thesis defining how the chapters come together to form a cohesive whole —

[144] N. O. Essi *et al. Evaluation: A Systematic Approach.* (2006)

this is shown in Figure 3.4.

Chapters one to three are carried out in series and permit clarification of the research. RQ1 is addressed with two concurrent activities (Chapters 4 & 5) that seek to identify the requirements of design democratisation from the perspective of the user and of the manufacturing capabilities of FDM. These are brought together to form the basis of the design methodology proposed in Chapter six. A first implementation of the methodology is presented in Chapter seven in order to select and verify an appropriate toolset and means of navigating the FDM search space. Capability profiling underpins this tool and functionality of this is proposed in Chapter eight. The instantiation and subsequent validation of the proposed design methodology takes place in Chapter nine in the form of design case studies. These are then discussed in Chapter ten to understand if and how design democratisation is achieved. Chapter eleven determines whether the research aims and research questions have been achieved.

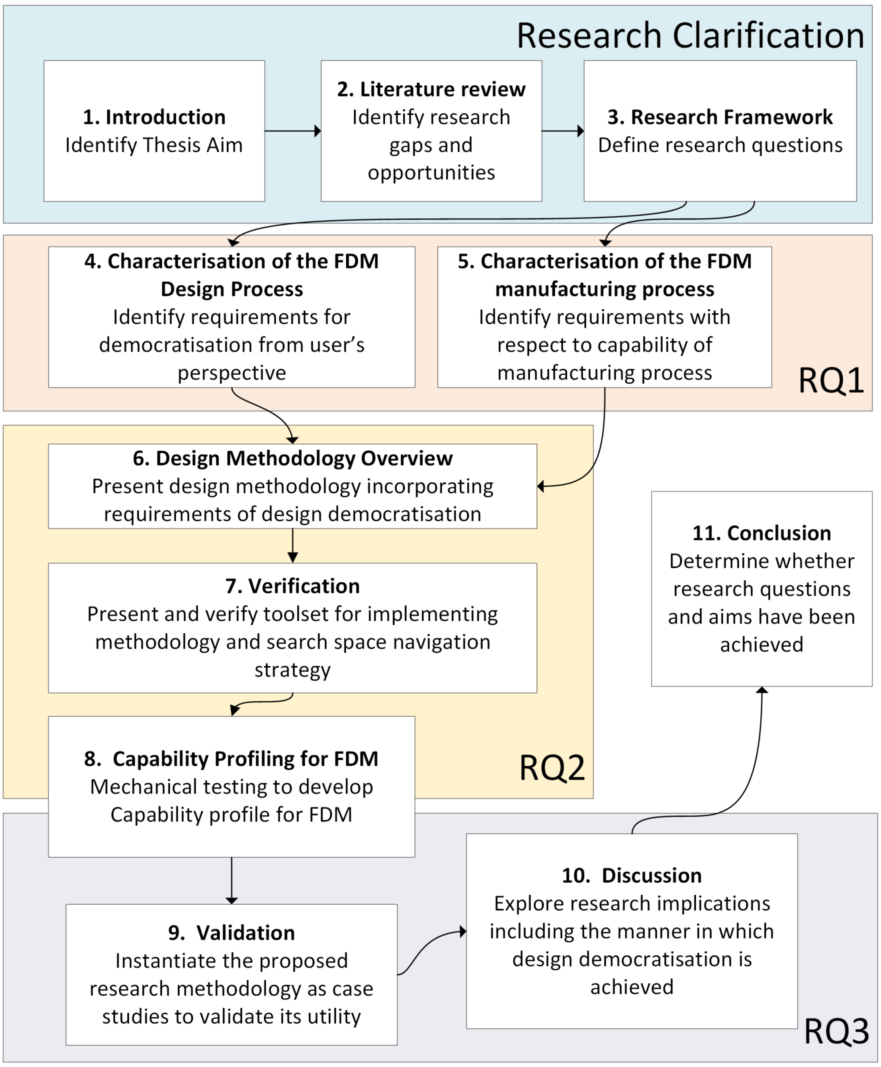


Figure 3.4 *Research map with corresponding RQs, Chapters and their content*

3.5 Chapter Summary

This chapter has defined a research framework that will be followed in this thesis. This was chosen as Blessing and Chakrabartis' Design Research Methodology. Its application to the research is summarised in Table 3.2 where the separate stages of the methodology are broken into research activities and the corresponding chapters where these can be found.

Table 3.2 *Summary of applied DRM with research activities and their corresponding chapters*

DRM Stage	Research Question	Research Method	Chapters
Research Clarification	N/A	Review of Design, Democratisation, Distributed manufacturing, existing design methods for FDM, state-of-the-art of design for FDM	1 &2
Descriptive I	**RQ1** — *What are the requirements of democratising design for FDM?*	Synthesis of requirements of design democratisation via characterisation of FDM design and manufacturing processes	4 &5
Prescriptive I	**RQ2** — *How can generative design approaches be used to augment the existing capabilities of design platforms?*	Development of a design methodology that can meet the requirements of design . Subsequent implementation of the methodology in the form of case studies	6, 7 & 8
Descriptive II	**RQ3** — *How is design democratised by incorporating a generative design approach into existing design platforms?*	Through the case studies, the efficacy of the implemented design methodology is analysed and findings are used to elucidate how design is democratisation is achieved.	9 & 10

Chapter 4

Characterising the FDM design process

The previous chapter defined a research framework that would be adhered to in order to achieve the thesis' research aim. This chapter constitutes part of the Descriptive I study of Blessing & Chakrabarti's DRM. It seeks to understand the requirements of design democratisation from the perspective of a prospective user. To achieve this it has the following objectives:

1. Identify who uses 3D printers in order to determine who is excluded from their use currently.
2. Understand the common design tasks carried out with FDM and elucidate the fundamental design challenges overcome in these tasks.
3. Identify the underlying design process followed to produce useful parts with FDM.
4. Identify steps in the design process that contribute to the level of difficulty and hence act as barriers to the democratisation of design.

4.1 Studies

To achieve this a literature review and two studies are undertaken. The first objective is achieved by reviewing literature on current users of 3D printers. To meet the second objective, a survey of a design repository is carried out to elicit the typical design challenges overcome with 3D printing. The final two objectives are addressed through a design study seeking to characterise the design process for FDM, and in doing this, the steps contributing to difficulty can be identified.

Figure 4.1 gives an overview of activities carried out within the two studies and their intended outcomes.

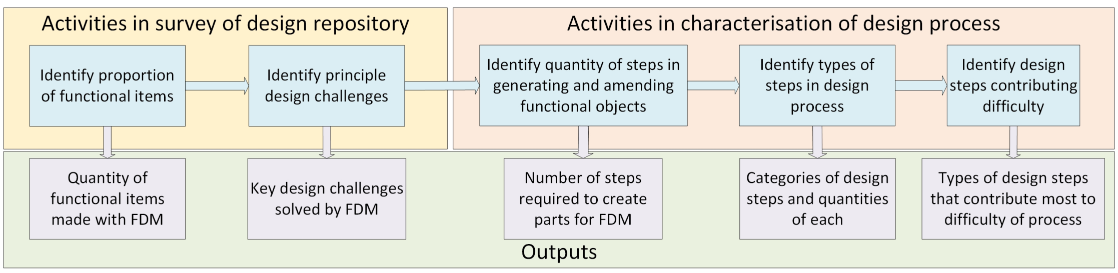


Figure 4.1 *Process diagram for chapter*

The results of these studies provide the basis for defining some of the requirements of design democratisation and allows the elucidation of the requirements for a methodology that can enable the democratisation of design.

4.2 Who to democratise design for

To identify the requirements of the democratisation of design, it is important to identify who design is to be democratised for and elucidate some key traits that would indicate what their current capabilities are. This section will consider this from the perspective of educational attainment and technological familiarity.

Educational attainment of people who use 3D printing are as follows - 10.2% secondary school,36.7 % bachelors, 41.4% masters, 11.2%1 doctorate [32]. This when compared to proportion of people who have a degree which in the UK is 27.2% [145] shows that the vast majority do not use 3DP technology. The democratisation of design is about allowing more people to design for themselves. Therefore in achieving this, an appropriate level of education to assume is at most secondary school qualifications. This can provide a target educational threshold.

In addition to levels of education, it is important to consider the typical traits of those who design would be democratised for. Generations Y & Z constitute the worlds largest demographic accounting for roughly 59% of the world's population [146].

Those in Generation Y are known as technology wise and can be considered digital natives. They are born between 1982 and 1994 and technology is part of their everyday lives. This relationship with technology is taken a step further with Generation Z who are born between 1995 and 2010, directly into tablets and smartphones. This generation are growing in'a highly sophisticated media and computer environment' [147] [148]. As such they can be considered comfortable with the use of technology. For this reason, and given the large proportion of population that they constitute, Generations Y & Z are realistic targets for design democratisation.

The principal implication this has on the requirements of a design tool are that it is likely to need to address the functional aspects of design democratisation (i.e. how can the generation of a satisfactory part be enabled) rather than those associated with user interfaces - where the development of previous straightforward design tools has been more focussed. This requirement places a limitation

[32] Sculpteo. *The State of 3D Printing 2019 Edition.* (2019)
[145] C. Ball. *Most people in the UK do not go to university – and maybe never will.* 2013
[146] Bank of American and Merill Lynch. *Thematic investigating: New kids on the block.* (2016)
[147] WJ Schroer. *Generations X,Y, Z and the Others.* 2019
[148] Iberdrola. *From the baby boomer to the post-millennial generations: 50 years of change.* 2019

on the method in that it will not accommodate the needs of 'older' users, those from generation X for example, that do not have such strong existing technological familiarity. This is considered acceptable due to the large proportion of the world's population that comprise generations Y and Z as mentioned previously.

In summary, design democratisation will be targeted at people who have existing familiarity with technology but are assumed to have an educational level lower than degree level. These aspects will be factored in when characterising the FDM design process and identifying where in this process difficulty occurs.

4.3 Types of design tasks for 3D printing

To enable mapping of the FDM design process it is first necessary to understand the types of design problem that are typically overcome by products manufactured by FDM. To investigate this, analysis of the 81 most popular items on Thingiverse [101] and items were categorised against:

- *Whether they are functional or novel* - examples of functional items included a G-clamp, lamps, a Raspberry Pi Case and parametric nuts and bolts. Novelty items included a Millennium Falcon, spinning top and an Iron Man suit. Whilst FDM is a powerful manufacturing tool, it is thought to be largely used to make models and trinkets. This categorisation will allow the proportion of functional items to be identified, as well as distinguishing the design problems faced by functional and novelty items respectively.
- *The principle design problem that need to be overcome* - these are explored in greater detail in Table 4.1. If an item consisted of additional parts that were not all 3D printed, the design problem was assigned with respect to the 3D printed parts.

Additional information taken from the design repository included total downloads and date added in order to create a normalised metric of downloads per month which would allow a comparison of popularity across the items.

The design challenges were defined based on the items surveyed. Whilst there are arguably more that could be assigned to 3D printed parts, for example thermal insulation, these six categories were deemed to be satisfactory as they were able to accommodate all items considered. The key design challenges along with examples are presented in Table 4.1.

Items were all categorised according to the two principle design challenges faced

[101] MakerBot. *MakerBot Thingiverse*. 2019

Table 4.1 *Design Mode Definitions*

Design Problem	Definition	Example
Fit/Interface	Limits, fits and interfaces. How a component interacts with another topologically.	1. G-Clamp – operation is determined by a thread. 2. Raspberry Pi case – requires the components to fit together.
Load	The way an object responds to load. This could be to resist breaking under a given load or to deflect a certain amount.	1. G-Clamp – needs to provide a specific clamping force. 2. Spray can holder must be able to hold weight of can. 3. Parametric pulley must be strong enough to transfer a given load.
Size	How a component interacts with another on a macro scale.	1. Lamp Shade must be of correct size to contain light fitting. 2. Raspberry Pi case must be correct size to fit Raspberry Pi. 3. Bottle Cap must be appropriately sized for a particular bottle. 4. Mask must be appropriately sized to fit on a face.
Functional Shape	How a component's shape affects its function (behaviour). This is not form, as all of the design modes listed will result in change to the form of the object.	1. Spinning top shape alters its inertia and ability to spin. 2. Vacuum cleaner adaptor changes the airflow. 3. Sundial blocks light to show the time.
Aesthetic Shape	How a component appears aesthetically.	1. Iron Man suit needs to look like Iron Man. 2. Vase must look good to complement its contents.
Mass	When variations in a components mass can alter its behaviour. This is important with 3D printing as infill and shells are variable.	1. Quadcopter chassis must be light enough to fly. 2. Mass and distribution of mass of a spinning top will alter its ability to spin.

in their design, except for a few novelty items whose sole design objective was that of aesthetic shape. All of the design modes result in alterations being made to the form of the item.

Of the 81 items surveyed, 24 were 'novelty' and 57 'functional' corresponding to 70% being functional. When the items were normalised with respect to downloads per month, 61% percent of the 169,000 monthly downloads were for functional items.

Figure 4.2 shows how the design challenges vary as a percentage of total downloads per month for the surveyed items and also separately for functional and novelty items. From Figure 4.2 it can be concluded that the most important design mode for novelty items is (perhaps unsurprisingly) aesthetic shape and secondly fit. For functional items, the crucial design problems are identified as fit, load and size. Combined they account for over 75% of the design modes identified.

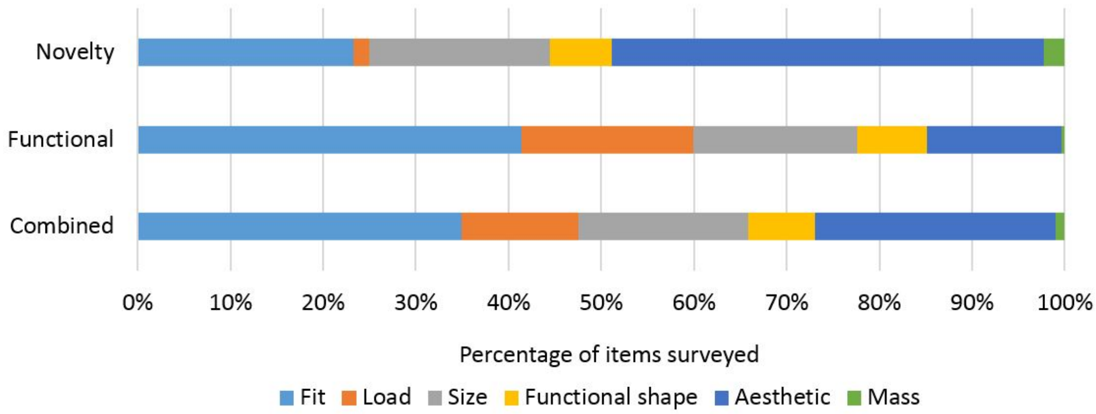


Figure 4.2 *Distribution of principle design modes of the surveyed items*

In addition to determining the types of products manufactured by FDM, it is also important to ascertain what phases of the design process they correspond do. A study undertaken by Shewbridge et al. identified uses for 3D printing in the home [149]. Only 4% of the items people would wish to make via 3D printing were 'new' times. The majority were to replicate, repair or replace existing items. If contextualised with respect to the Pahl and Beitz framework this corresponds to the embodiment and detail phases and is classified as *variant* design.

[149] R. Shewbridge *et al. Everyday Making: Identifying Future Uses for 3D Printing in the Home.* (2014)

4.3.1 Concluding remarks

The key design problems for 3D printed items have been identified for the items surveyed as a total and also when broken down into functional and novelty categories. In democratising design and manufacture we are concerned with the manufacture of useful, functional items. As a result, the following sections examine the design process in detail for the design of a series of 3D printed components for the tasks of fit, size and load. It was also found that the majority of tasks people would undertake with FDM can be considered variant design.

4.4 The design process for FDM

Using the previously identified common design challenges for FDM, the study continued by looking at the activities that an individual would need to take in generating a object to overcome them.

4.4.1 Method

The study was performed by the author who is proficient in 3D printing methods and technology (having designed and built a 3D printer [150]) and engineering holding an MEng in Mechanical Engineering. The studies focussed on functional items defined by the design problems of fit and size, the second of fit and load and the third on load and size. The items designed are explained in Table 4.2 and depicted in Figure 4.3. The first objective of these studies was to examine the categories and number of design steps (actions) undertaken. The design tasks were iterative and modelled from scratch using Autodesk Inventor 2016. Each item had a set design goal that had a simple pass / fail criterion. This is included in Table 4.2. After each iteration the item was printed and tested with a decision made to whether it met the requirements and on the design strategy if it required improving. Design iterations were continued until a satisfactory object was manufactured.

Table 4.2 *Design study overview*

	Fit and Size	**Fit and Load**	**Load and Size**
Object	Bottle Cap	Table hanger	Coat Hook
Explanation	Design challenges are fit of thread and size to fit specific bottle	Object is required to withstand a given load, and fit onto the table edge	Required to hold a given load applied by an item of given size
Success criteria	Successfully prevent leakage from a bottle	Hold load of 20kg	Hold load of 20kg

Various methods were considered for the logging of steps during the design process. An Issue Based Information System (IBIS) approach was considered though was disregarded as it would not permit a clear way to present and analyse the information [151]. Integrated Definition Model (IDEF) protocols were also considered but these were un-suitable for capturing the level of detailed required

[150] M. Goudswaard *et al. Realisation of self-replicating production resources through tight coupling of manufacturing technologies.* (2017)

[151] D. Noble and H. W. Rittel. *Issue-Based Information Systems for Design.* 1988

(a) *Bottle Cap* (b) *Table Bracket* (c) *Hook*

Figure 4.3 *Objects used for design study*

[152]. Protocol analysis techniques were also examined though these were more concerned with creative and complex design tasks [153] whereas we are more concerned with the individual, small scale processes and decisions which permit the design of what is arguably a very simple object.

As no existing method was found that could adequately capture the required data, one was created. A spreadsheet was be used to document all activities carried out during the design tasks. Table 4.3 shows a sample extract of the information recorded during each task. The columns correspond to the following categories:

- **Action** - the objective of a group of design steps.
- **Computer Interaction** - non CAD specific software interaction.
- **Inspection of part** - interaction with physical object to find identify feature / find information.
- **Issue** - e.g. identification of a problem that requires resolving.
- **Options** - potential pathways to issue resolution.
- **Decision** - as to which option is chosen.
- **Justsification** - reasoning for option selection.
- **Information / Data** - elucidated within an action and may be re-called in subsequent design steps.

[152] K. B. S. I. (KBSI. *A Structured Approach to Enterprise Modeling & Analysis.* 2016
[153] N. Cross *et al. Analysing Design Activity.* (1996)

Table 4.3 *Extract from Case Study 1 to demonstrate recorded information during design*

Action number	Action	Computer Interaction	Inspection of part	Issue	Options	Decision	Justification	Information/Data
1		Open Inventor						
2		Generate New Part						
3			Inspect Existing cap to identify features					1) Female Thread 2) Textured edge to allow gripping 3) Tapered open end of cap to allow placement
7				How to model bottle cap?	1) First model cylinder then subtract another cylinder of material from inside 2) Revolve a 2D sketch to make cap shape	1	Easiest way to model cap, easy to modify as well	

Table 4.4 *Extract from case study 1 to demonstrate information recorded post design task*

Action number	Outcome	Category of outcome	Depth of knowledge required	Technical Ability	Technical Understanding
1	Inventor open	Software operation	Low	1	0
2	New part generated	Software operation	Low	1	0
3	Features identified	Observation	Be able to identify thread and the purpose of the textured edge	1	3
7	Decision made for design strategy to model cap	Decision	CAD knowledge of options to generate the required shape, and make a reasoned decision to which is the best method	4	0

Post design task, further columns in the spreadsheet were then populated. These were not filled in at the time of design so as to minimise disruption to the design process. An extract is shown in Table 4.4. The additional columns populated are defined as:

- **Outcome** - what was achieved through undertaking this design activity.
- **Category of outcome** - grouping of outcomes.
- **Depth of knowledge required** - qualitative assessment of the requisite knowledge necessary to carry out the design step .
- **Technical ability** - ability to undertake a necessary action.
- **Technical understanding** - elucidation of a suitable course of action to take.

The steps were finally categorised into five categories that corresponded to areas of the design process where democratisation could occur:

- **Software Interaction** - e.g. opening a program, saving a part or exporting a file.
- **Hardware Interaction** - e.g. operating a 3D printer.
- **Decision** - e.g. choosing a course of action, deciding how to use the software to achieve a goal.
- **Observation/Measurement** - e.g. testing an item or identifying features on an existing object.
- **Geometry alteration** - generating or changing 2D or 3D geometry.

This categorisation permits the elucidation of the proportion of steps from each category that take place during a design task.

To investigate the most challenging step for the hobbyist/consumer, the three case studies were further post processed to consider the level of difficulty associated with each design step.

Table 4.5 *Definitions of defined difficulties*

Difficulty	Description	Technical Ability Example	Technical Understanding Example
0	Not relevant to task	-	Change a dimension
1	Requires everyday knowledge	Open Autodesk Inventor	Identify what bracket needs to fit to
2	-	Open existing sketch	Elicit how a hook will hang an item
3	Requires technical knowledge that could be learned through hands on experience	Apply fillet to corner	Identify measurements that are required for design
4	-	Use inventor offset function	Decide shape profile to minimise stress concentrations
5	Requires knowledge that was taught in engineering degree	Edit thread profile to better suit requirements	Decide strategy to reduce deflection under load

Difficulties from 0-5 were assigned for each design step with respect to technical ability (A) and technical understanding (U). Ability encompassed difficulties associated with use of the software and hardware. Understanding encompassed broader knowledge tailored towards the function and behaviour of the item. For example deciding to add a fillet to reduce stress concentrations requires technical understanding whereas amending the model to add a fillet requires technical ability. It is important to distinguish between these as it is likely that democratisation of one would require very different interventions to the other. This distinction also enables framing of exactly who we will be democratising design for based upon their specific needs. The difficulties assigned, explanations for levels along with examples are shown in Table 9.6.

The difficulties were then totalled in order to give a value that represented the technical ability or understanding required to complete a given iteration. This could then be split further to see what category of step (e.g. decisions) contributes most to the difficulty of the design process.

4.4.2 Results

Figure 4.4 shows the cumulative number of steps for each design process broken down into the various categories.

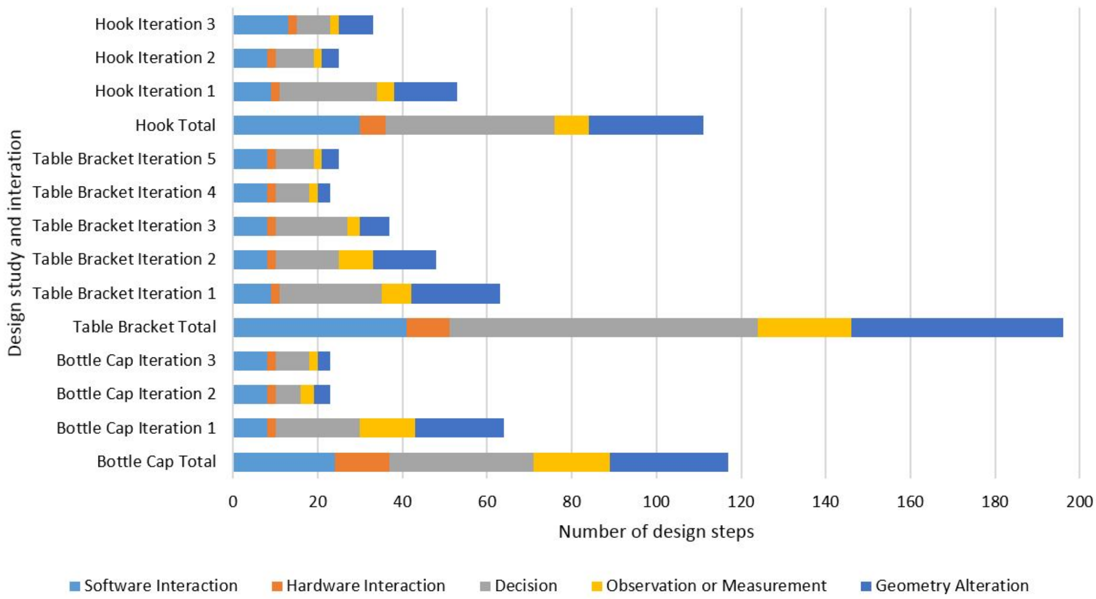


Figure 4.4 *Number of design steps for each case study and iteration*

The types of design steps when designing for 3D printing have been identified as software interaction, hardware interaction, decisions, observations/measurements and geometry alteration. From Figure 4.4 we can conclude that:

- Generating geometry requires more steps than altering geometry.
- Decisions account for the majority of steps in all studies and iterations.
- Observations and measurements greater in geometry generation than in subsequent iterations.

- Number of hardware and software steps remain consistent across iterations as would be expected as there are a set number of steps associated with saving/opening files, exporting STLs setting parameters and printing. Variation step by step will therefore be in the proportions of decisions, observations and measurements and geometry alterations.

Figure 4.5 shows the totals of technical ability and understanding for each design task both cumulatively and broken down for each design iteration. Table 4.6 shows a heat map demonstrating the average difficulties of all processes (both cumulatively and broken down for design iterations)and also for the individual design categories.

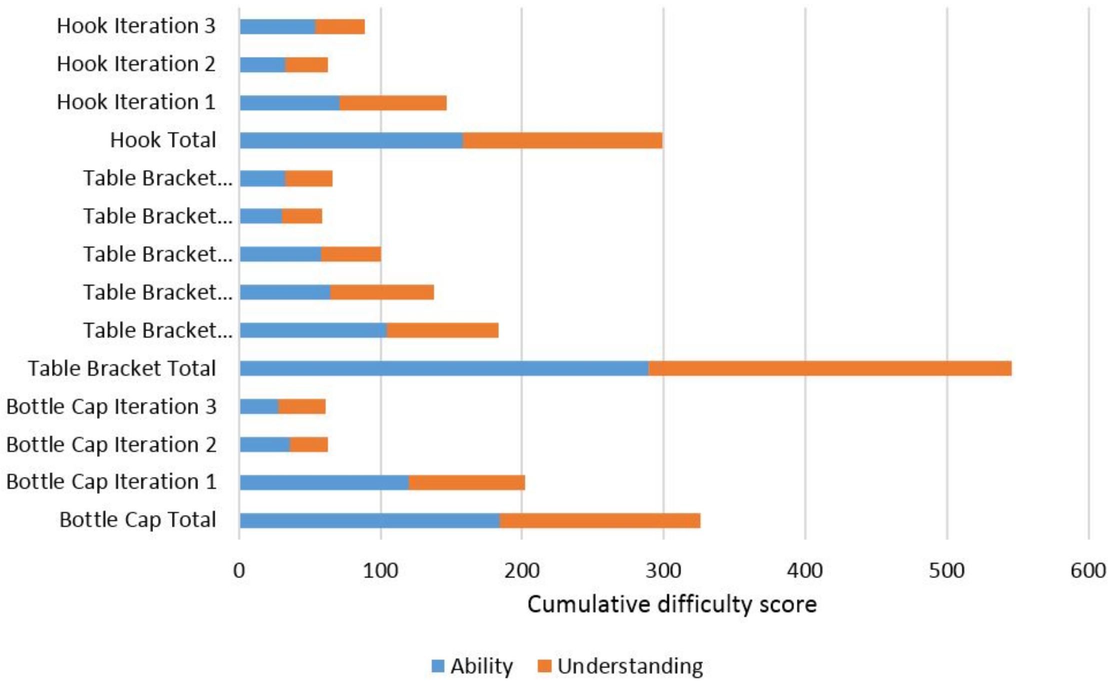


Figure 4.5 *Difficulty scores for ability and understanding*

From Figure 4.5 it can be concluded that for the different design problems and across different design iterations the split of total difficulty is fairly equal for understanding and ability. Average for understanding is consistently higher than that of ability. Suggesting that the greatest difficulty in design is not in the use of specialist software but the background knowledge of how items function.

Table 4.6 identifies four categories that consistently provide difficulty.

- **Understanding of observation and measurement** - e.g. knowing what to look for or measure
- **Technical ability based decisions** - e.g. reasoning on which functions to use to achieve a given goal.

Table 4.6 *Areas of relative difficulty in the design process (Ability (A), Understanding (U))*

		Software Interaction		Hardware Interaction		Observation & measurement		Decision		Geometry		TOTAL	
		A	U	A	U	A	U	A	U	A	U	A	U
Bottle Cap	Iteration 1	1.9	0.0	2.0	0.0	1.6	3.2	3.3	2.9	3.2	2.0	2.7	3.0
	Iteration 2	1.6	0.0	2.0	0.0	2.0	2.3	5.0	4.0	3.0	0.0	2.3	3.4
	Iteration 3	1.4	0.0	2.0	0.0	2.0	4.0	3.0	3.6	3.0	0.0	2.0	3.7
	Design Total	1.6	0.0	2.0	0.0	1.7	3.2	3.4	3.3	3.1	2.0	2.5	3.2
Table Bracket	Iteration 1	1.7	0.0	2.0	0.0	2.2	3.0	3.5	3.1	2.9	0.0	2.5	3.0
	Iteration 2	1.8	0.0	2.0	0.0	2.3	3.3	3.0	3.7	2.2	0.0	2.1	3.5
	Iteration 3	1.8	0.0	2.0	0.0	2.0	2.7	2.8	3.1	2.7	0.0	2.3	3.0
	Iteration 4	1.8	0.0	2.0	0.0	3.0	3.0	3.0	3.3	2.0	0.0	2.0	3.2
	Iteration 5	1.8	0.0	2.0	0.0	3.0	3.0	3.0	3.4	2.3	0.0	2.1	3.3
	Design Total	1.7	0.0	2.0	0.0	2.3	3.0	3.1	3.3	2.5	0.0	2.3	3.2
Hook	Iteration 1	1.7	0.0	2.0	0.0	1.5	3.0	3.0	3.2	2.5	0.0	2.2	3.2
	Iteration 2	1.8	0.0	2.0	0.0	1.5	2.5	3.0	3.6	1.5	0.0	1.8	3.3
	Iteration 3	1.8	3.0	2.0	0.0	2.0	3.0	3.0	3.3	2.5	3.0	2.1	3.2
	Design Total	1.7	3.0	2.0	0.0	1.7	2.9	3.0	3.3	2.3	3.0	2.1	3.2

- **Technical understanding based** - e.g. how change/modify a structure to reduce stress concentrations.
- **Technical ability to amend geometry** - using the software to achieve a given goal.

From Figure 4.5 we can also conclude that generating geometry (iteration 1) requires more steps than editing geometry (subsequent iterations) and shows that the average total difficulty per design iteration remains fairly consistent.

4.5 Implications for democratising design

The objective of this chapter was to explore the design processes of functional parts manufactured through FDM in order to elucidate the requirements of a democratising design methodology from the perspective or prospective end users. A number of outcomes have implications for the DoD.

The first objective was to identify who currently uses technologies such as FDM, who is currently excluded from using them and as such could subsequently be a prospective user for design democratisation. This permitted the formation a target persona for whom design would be democratised. This was based upon a person being a member of either generation Y or Z (hence a competent user of technology) and with a secondary school level education.

The identification of common items manufactured by FDM and the fundamental design problems that need to be overcome in their design was the second objective of the studies undertaken. It was found that 61% of items by download count were functional, revealing that manufacturing of useful parts via FDM is already significant and that the proposition of democratising design via FDM is valid. The principal design problems of FDM items were found to be fit, load and size. It was also noted that the majority of items people would wish to manufacture via FDM would correspond to variant design tasks.

The third objective sought to map the underlying design process followed to produce useful parts with FDM. The steps taken were categorised in order to understand the types and quantities of tasks undertaken during the design process. This allowed a comparison of the design steps taken between the different design tasks and design iterations. It was found that it takes fewer steps to amend geometry than it does to generate geometry suggesting that amending existing models from design repositories would be an easier and more efficient means to generate objects than designing from scratch. This is congruent with the need to permit variant design rather than design new objects.

The final objectives were to identify the steps in the design process that contribute most to the level of difficulty and thus potential challenges for democratisation. In particular, technical ability and technical understanding were evaluated in order to examine the relative levels of proficiency required. The areas contributing most to the level of difficulty were found to be technical understanding for observations and measurements, technical ability and understanding for decision making and technical ability for amending geometry. These therefore represent the key areas that need to be addressed in order to democratise design.

With respect to the average difficulty of design step, understanding is the more challenging issue occurring in more categories than ability, however, cumulatively the contribution to total difficulty is relatively equally split between ability and understanding.

To convert these findings into a requirement for the democratisation of design it is necessary to identify which of these activities would provide the biggest barrier to design for FDM for the persona identified in Section 4.2. Generations Y & Z are identified as being technically savvy and thus are assumed capably of operating systems and navigating user interfaces. Therefore technical understanding will provide a bigger barrier, especially considering the assumed secondary level of education. Technical understanding for observations and measurements and decision making are therefore the key areas that need addressing in order to enable the democratisation of design. It is necessary to provide guidance in the decision making process, meaning a tool would need to understand how changes in a parts behaviour or function can be brought about by alterations to its geometry. It will also be necessary to assist the user in validating and evaluating the designs they generate.

4.5.1 Requirements for the democratisation of design

The conclusions from this chapter allow the formulation of two requirements for a methodology that can enable the democratisation of design for FDM. To recap, these are based upon the identified persona for democratisation, the key design challenges overcome by FDM, the design phases corresponding to household items manufactured by FDM and lastly the areas of difficulty identified in the characterisation of the design process.

The requirements based upon these are as follows:

1. **To permit a user to replicate, repair or improve existing items** - A democratising design methodology would not need to create novel items *a priori*. Of the design tasks people would carry out using FDM, only 4% involved the creation of new items. The majority were to replicate, repair or improve existing items [149]. If contextualised with respect to the Pahl and Beitz framework, a democratising design strategy would therefore need to cover the embodiment and detail stages [154].
2. **To make reasoned design decisions on behalf of the user** - the work undertaken in this study has identified that, whilst taking more design steps, generating functional objects in CAD is as difficult as amending geometry. This signifies that even though a democratising design methodology doesn't need to permit the creation of novel items (as per the previous requirement), there is still a need to make reasoned design decisions on behalf of the user. A democratising design methodology must therefore incorporate this.

These and subsequent requirements will frame the direction and development of a design methodology in later chapters.

4.6 Concluding remarks

This chapter has presented a study undertaken to identify areas in the design process for FDM that if improved would facilitate the democratisation of design.

[149] R. Shewbridge *et al. Everyday Making: Identifying Future Uses for 3D Printing in the Home.* (2014)
[154] G. Pahl and W. Beitz. *Engineering Design.* (1984)

These were found to be: technical understanding to make observations and measurements; technical ability and understanding to make design decisions; and, technical ability to amend geometry. In addition to this, the study found that the principle design problems of objects typically manufactured by FDM are fit, load and size.

The design process for items representing these design problems was mapped and steps were categorised with respect to type of action and assigned difficulties corresponding to technical understanding and to technical ability. This permitted the identification of difficult steps in the design process and their relative distribution of occurrence over the design process.

The discussion focussed on the consequences of the study's findings and presented a further requirement for a design methodology that enable the democratisation of design for FDM.

Two additional requirements of a democratising design methodology were formulated.

Chapter 5

Characterising the FDM manufacturing process

Previous chapters have identified a need to provide decision support in order to the democratisation of design for FDM. To provide this support in the manufacture of functional parts it is necessary to understand the capability of the manufacturing process itself. Correspondingly, this chapter seeks to characterise the FDM manufacturing process. This consists of a comprehensive review of extant knowledge of the FDM process, the identification of immediate gaps and undertaking of mechanical testing to clarify these.

5.1 The FDM Manufacturing Process

In order to characterise the FDM manufacturing process, it is first necessary to provide an overview of it.

FDM builds parts additively layer by layer. Plastic filament is melted and extruded through a nozzle creating a 2.5D layer of material (slice) on the print bed. The nozzle is then raised and the next slice is deposited on top. Continuing in this way, a part is manufactured. Whilst external geometry of the part is defined by a CAD file, the nature of these layers has a large impact on both the geometric and mechanical properties of a manufactured part. Layers are affected through amendment of manufacturing parameters. A number of these are demonstrated Figure 5.1. The internal structure of a part can also be amended by changing a part's infill. Available infill patters from Ultimaker's Cura slicing software are shown in Figure 5.2.

The layer-wise deposition of material makes the manufacturing process inherently anisotropic. This, other material properties typical of components manufactured via FDM and the impact manufacturing parameters have on properties will be explored in the following section.

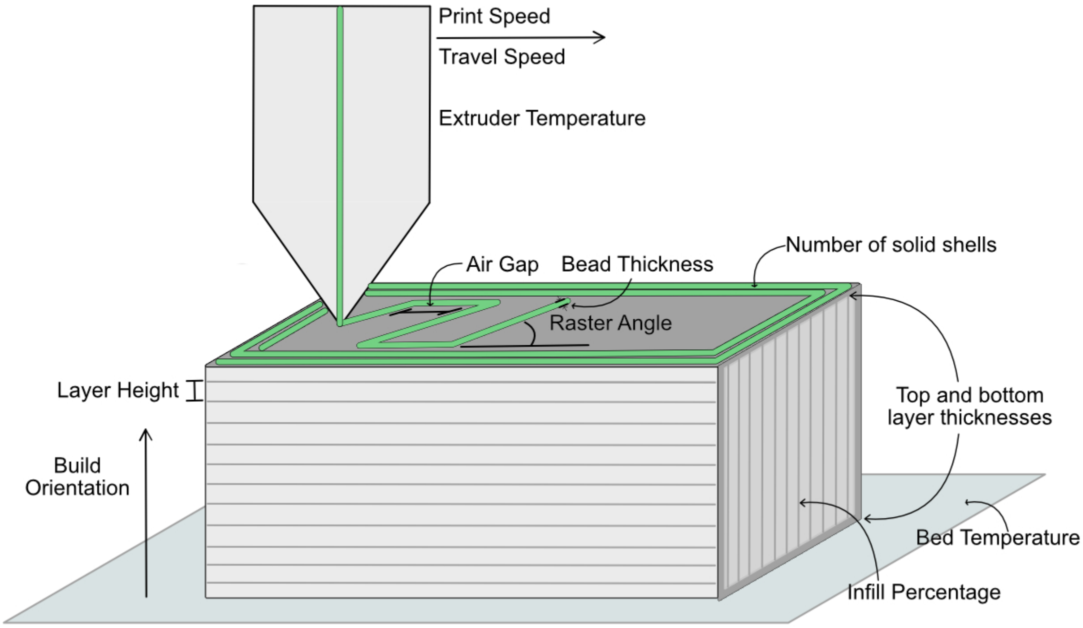


Figure 5.1 *FDM manufacturing parameters*

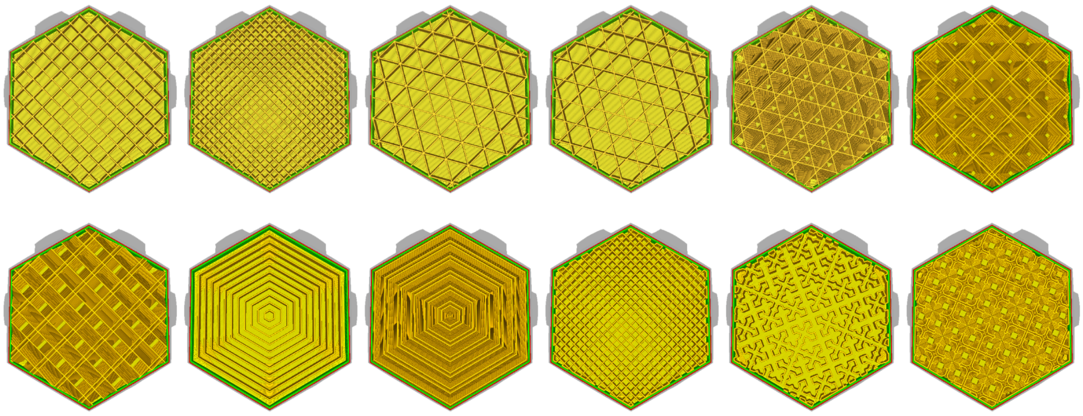


Figure 5.2 *FDM Infill patterns from [155]*

5.2 Existing FDM process knowledge

Early applications of FDM as a manufacturing technology were largely aesthetic or for prototyping, with a focus on high quality prints to generate consistent, geometrically accurate parts with good surface finishes but with little consideration of their functional performance. As such, the impact that manufacturing parameters have upon geometric properties are relatively well understood. General geometric accuracies for FDM are +- 0.2 to 0.5 mm are stated for FDM manufacturing [156]. Part accuracy is increased by decreasing layer height, de-

[156] B. Redwood *et al. The 3D Printing Handbook - Technology designs & applications.* (2017)

creasing nozzle width and decreasing print speed. Causes for geometric inaccuracies and inconsistencies can be broken down into the following categories [157]:

- **Design / Software related inaccuracies** that include:
  - Error accumulation in the conversion from CAD format to STL.
  - Tool-path generation being based upon the centre of the extruder and not accounting for raster-width.
  - A staircase effect in the Z direction caused by the discrete layers.
- **Process related inaccuracies** including improper calibration of printer.
- **Material related inaccuracies** such as shrinking and warping.

Given this existing understanding, various methods of geometric benchmarking have been proposed to assess these elements of an FDM printer's capability [158]. More recently an ISO standard has been published defining test artefacts for the geometric benchmarking of Additive Manufacturing processes [159]. These allow quantification of a printer's capability, the subsequent identification of the part's that can be manufactured by a given printer and the accuracy that might be expected.

As the technology has developed further and FDM has become more capable of producing structural parts, studies have sought to evaluate and characterise the relationship between mechanical properties and manufacturing parameters. From these studies a number of empirical relationships have been deduced:

1. Studies of layer height have generally found that larger layers increase part strength [160] [161] [162] [163] [164] [165].
2. Studies of part build orientation have revealed that parts are found to be

[157] E. Umaras and M. S. Tsuzuki. *Additive Manufacturing - Considerations on Geometric Accuracy and Factors of Influence.* (2017)
[158] L. Rebaioli and I. Fassi. *A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes.* (2017)
[159] International Standards Organisation (ISO). *ISO/ASTM 52902:2019 (ASTM F42) - Additive manufacturing - Test artifacts - Geometric capability assessment of additive manufacturing systems.* 2019
[160] B. M. Tymrak *et al. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions.* (2014)
[161] G. C. Onwubolu and F. Rayegani. *Characterization and Optimization of Mechanical Properties of ABS Parts Manufactured by the Fused Deposition Modelling Process.* (2014)
[162] A. Alafaghani *et al. Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach.* (2017)
[163] D. Croccolo *et al. Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30.* (2013)
[164] A. K. Sood *et al. Parametric appraisal of mechanical property of fused deposition modelling processed parts.* (2010)
[165] A. Lanzotti *et al. The impact of process parameters on mechanical properties of parts fabricated in PLA with an open-source 3-D printer.* (2015)

weakest in the direction of build [160] [161] [162] [163] [164] [165].

3. Parts are strongest with raster angle in direction of the applied load and increased raster width increases part strength [161] [163] [166] [164] [165].
4. A negative air gap is found to increase part strength [161] [163] [164].
5. An increased infill percentage is found to increase part strength [162].
6. An increase in the number of solid shells increases part strength [163] [165].
7. Extrusion temperature is shown to greatly affect the mechanical properties of the printed parts with distinct optimum extrusion temperature ranges existing for different materials [162] [167].
8. Mechanical properties are found to vary significantly with material type, build [160] [161] and colour [167].

Whilst a significant body of work exists, the understanding of mechanical properties is lower than that of geometric accuracy, in part due to the large number of parameters that impact them. Therefore, from the review of existing literature, a number of research gaps requiring addressing can be identified.

While the reported studies have established a number of empirical relationships, many used relatively small sample sizes (of 3 [161] [162] [164] [165] or 5 [163] [166]) with little reporting of the process variability, or identified very high variability in mechanical properties [165] compared to the raw material [166]. As a consequence of this, while the empirical relatives are directed, no magnitudes have been established with any confidence. A research gap is therefore identified as the identification of the variation in Ultimate Tensile Strength (UTS) for test pieces manufactured with identical material and process settings for a much larger sample size than those in previous studies. The need to clarify variability of the FDM process is specifically identified in a comprehensive review paper on the mechanical properties of parts manufactured via FDM [168].

Additionally, existing studies have largely tested according to ASTM standards for material testing (Tensile [169], Compressive [170] & Flexural [171]) and test the properties of the prescribed specimen which is assumed to be indicative of

[166] C. Casavola *et al.* *Orthotropic mechanical properties of fused deposition modelling parts described by classical laminate theory.* (2016)
[167] B. Wittbrodt and J. M. Pearce. *The effects of PLA color on material properties of 3-D printed components.* (2015)
[168] P Hemalatha *et al.* *Additive manufacturing: opportunities and constraints A summary of a roundtable forum held on 23 May 2013 hosted by the Royal Academy of Engineering Additive.* (2013)
[169] ASTM International. *Standard test method for tensile properties of plastics.* (2003)
[170] ASTM. *Standard Test Method for Compressive Properties of Rigid Cellular Plastics 1.* (2016)
[171] ASTM INTERNATIONAL. *ASTM D6272 - 10 Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending.* (2017)

properties of other shapes and sizes made of the same material. This assumption is currently un-substantiated by experimental evidence and, due to the layer wise construction of the manufacturing process, might not be valid. An additional research gap is therefore identified as eliciting the effect of shape and scale on the mechanical properties of parts.

Whilst a large number of empirical relationships between manufacturing parameters and mechanical properties, a variety of printers, polymers, slicing software and process parameters were used, meaning that the generalisation of existing results is very difficult [168]. It is therefore necessary to undertake a comprehensive testing regime on a single printer and material in order to determine conclusively the effect that all print parameters have on mechanical properties.

In light of these identified research gaps, the following sections detail experimental testing undertaken to determine the variation in UTS of tensile test specimens and also the effects of shape and scale on the mechanical properties of parts.

5.3 Variance determination

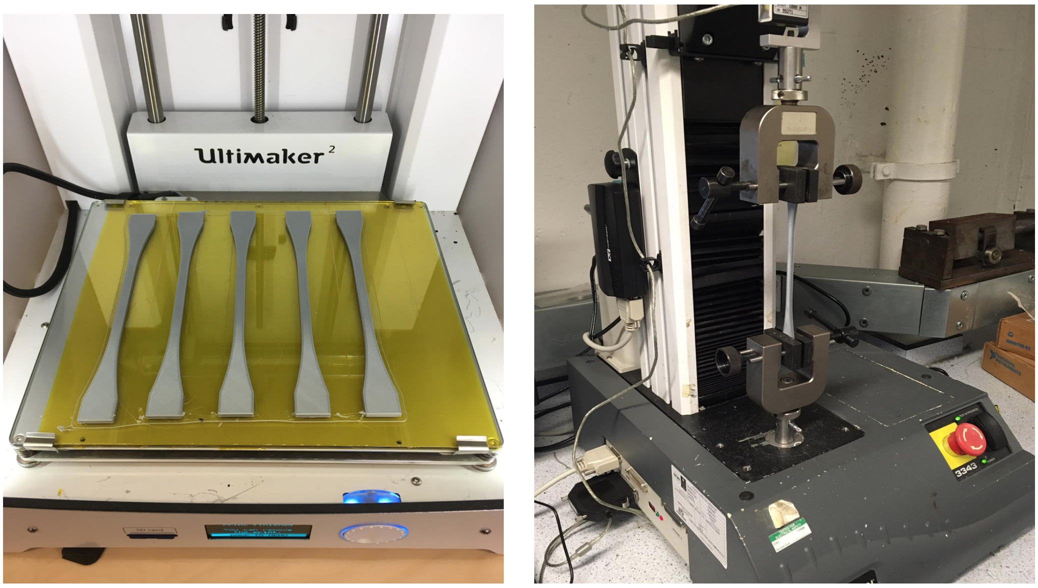
To determine the variance in mechanical properties of parts manufactured by FDM, tensile tests were undertaken with batch sizes larger than those found in existing literature.

5.3.1 Method

Test specimens were manufactured on an Ultimaker 2 using Ultimaker branded silver metallic Polylactic Acid (PLA) filament (shown in Figure 5.3a). Tensile tests were undertaken on an Instron 3343 tensile test machine with loads measured with a 1 kN Instron force transducer (shown in Figure 5.3b). Specimens were extended at a rate of 1mm/min until break.

Tests for variance determination used an altered ASTM:D638 [169] specimen (shown in Figure 5.4). A larger radius was added to reduce the likelihood of failure occurring outside of the reduced area (as also done by Croccolo *et al.* [163]). Specimen dimensions are shown in Figure 5.4. Eight batches of five samples were manufactured at infill values of 20% and 100%. These two values represent the

[168] P Hemalatha *et al. Additive manufacturing: opportunities and constraints A summary of a roundtable forum held on 23 May 2013 hosted by the Royal Academy of Engineering Additive.* (2013)
[169] ASTM International. *Standard test method for tensile properties of plastics.* (2003)
[163] D. Croccolo *et al. Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30.* (2013)



(a) *Batch manufacture of test specimens* (b) *Tensile test setup*

Figure 5.3 *Specimen manufacture and tensile test setup*

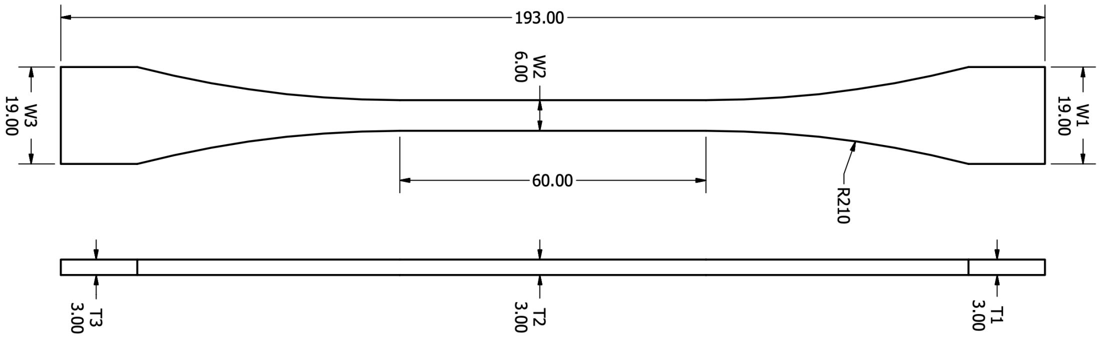


Figure 5.4 *Variance Test Specimen*

extremes with an infill below 20% resulting in an inconsistent top layer (compromising the overall shell) and 100% infill resulting in a solid part which negates the effect of infill pattern. Other print parameters of layer height, wall thickness, top/bottom thickness, infill pattern, extruder temperature, print speed, travel speed, print cooling and print sequence were all kept constant across the batches.

5.3.2 Results

The following table represents an extract of the collective specimen measurements and the results taken during the tensile tests (Table 5.1). Samples are considered collectively, and within the batches in which they were manufactured. Whilst all samples were printed with the same filament, different rolls were used for some of the samples. To account for any change in properties caused by this,

Table 5.1 *Results of tensile tests for variance determination. Standard Deviation is abbreviated to SD, percentage range is defined as the range divided by the mean expressed as a percentage*

SAMPLE	1	2	3	4	5	6	7	8	20% total	100% total
Infill %	20	20	20	100	100	100	100	100	20	100%
Sample size	5	5	5	5	5	5	5	5	15	25
Break Load (N)	539	567	592	686	766	766	755	749	566	745
SD (N)	16.5	23.8	26.8	29.8	38.1	27.1	35.1	34.8	30.7	44.5
% range	7	11	11	13	13	9	14	14	21	24
Max (N)	557	598	639	737	822	801	803	812	639	822
Min (N)	519	535	575	646	719	735	700	707	519.3	646.3
Range (N)	37.4	63.5	64.0	90.7	102	66.3	102	106	120	176
UTS (Mpa)	29.9	32.4	33.9	38.0	43.4	43.7	43.5	43.2	32.0	42.4
SD (MPa)	0.4	1.4	1.9	1.1	1.9	1.3	2.4	2.4	2.12	2.94
% range	4	12	14	8	12	7	17	17	24	26
Max (N)	30.5	34.5	37.0	39.4	46.1	45.3	46.5	47.3	37.0	47.3
Min (N)	29.4	30.7	32.3	36.2	41.0	42.1	39.2	39.9	29.4	36.2
Range (N)	1.1	3.8	4.7	3.2	5.1	3.2	7.3	7.4	7.6	11.1
W2 (mm)	6.02	6.03	6.01	6.04	6.03	6.03	5.98	5.95	6.02	6.01
SD (mm)	.019	.013	.023	.016	.018	.015	.040	.022	.018	.045
% Range	.66	.5	1	.66	.83	.7	1.7	1	1.0	2.3
Max (mm)	6.04	6.04	6.05	6.05	6.06	6.05	6.04	5.98	6.1	6.1
Min (mm)	6	6.01	5.99	6.01	6.01	6.01	5.94	5.92	6.0	5.9
T2 (mm)	3.00	2.90	2.90	2.99	2.92	2.91	2.91	2.92	2.93	2.93
SD (mm)	.067	.036	.048	.059	.027	.022	.063	.041	.066	.055
% Range	5.0	2.8	3.8	5.4	2.4	2.1	5.8	3.8	8	9
Max (mm)	3.09	2.96	2.97	3.09	2.95	2.94	3.01	2.99	3.1	3.1
Min (mm)	2.94	2.88	2.86	2.93	2.88	2.88	2.84	2.88	2.9	2.8
Mass (g)	5.05	4.93	4.98	6.79	6.77	6.76	6.78	6.83	4.98	6.78
SD (g)	0.12	0.08	0.07	0.15	0.09	0.08	0.02	0.02	0.100	0.083
% Range	5	4	4	5	3	3	1	1	8	5
Max (g)	5.19	5.03	5.09	6.96	6.89	6.88	6.80	6.86	5.2	7.0
Min (g)	4.92	4.81	4.89	6.62	6.66	6.65	6.75	6.81	4.8	6.6

additional samples were tested. For this reason, more sets of 100% infill specimens were tested than 20% infill – 5 and 3 respectively.

5.3.3 Discussion

The different samples demonstrated tensile strengths ranging by 24% to 26% percent when considered collectively and 4% to 17% intra-batch. This section explores the impact of extruder temperature fluctuations as a possible cause of the variability, whether the variability can be correlated to other part properties, and lastly how knowledge (characterisation) of this variability can be used when designing parts for manufacture via FDM.

5.3.3.1 Thermal imaging of FDM process

An exploratory study was carried out to investigate fluctuations in extruder temperature as a possible cause of the variation in tensile strengths for the identical samples. This is important as it enables variation to be determined as an issue with the manufacturing process. As such, it becomes an issue that can't be removed through the design process and moreover needs to be designed around.

This was investigated as Alafaghani *et al.* [162] found that changing the extrusion temperature set point resulted in significant alterations in tensile strength (shown in Table 5.2) and that filament temperature history has previously been identified as a critical parameter in dictating part strength [172]. This study sought to identify how the extruder temperature fluctuates around the set point during the duration of a print.

Table 5.2 *UTS vs extrustion temperature from Alafaghani* et al. *[162]*

Extrusion temperature (°C)	**UTS (MPa)**	**% change from 180°C**
175	28.59	-30%
180	40.58	0%
185	46.06	14%
205	43.79	8%

This effect was explored by analysing the change in extruder temperature during the print using a FLIR T650sc thermal imaging camera. A test piece of a single raster width was manufactured under the same conditions as those in the manufacture of the tensile test specimens and was filmed at 30 frames per second. The video was then analysed using FLIR IR Tools+ software. Average, maximum and minimum temperatures were extracted from four regions: deposited filament (Bx2); high in the nozzle (Bx3); mid nozzle (Bx4) and nozzle exit (Bx5). These regions are shown in Figure 5.5.

Table 5.3 shows the measured results for temperature fluctuations in these areas. Over the course of a print the high and mid nozzle areas show roughly 2°C changes whilst the deposited filament and nozzle exit areas show fluctuations of almost 5°C. When coupled with the temperature effects shown in Table 5.2, a 5°C temperature fluctuation could give rise to a 14-30% change in UTS. Therefore, correlation is observed between extruder temperature fluctuations and UTS, suggesting temperature fluctuations could be a cause of the variation in mechanical properties.

[162] A. Alafaghani *et al. Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach.* (2017)
[172] Q. Sun *et al. Effect of processing conditions on the bonding quality of FDM polymer filaments.* (2008)

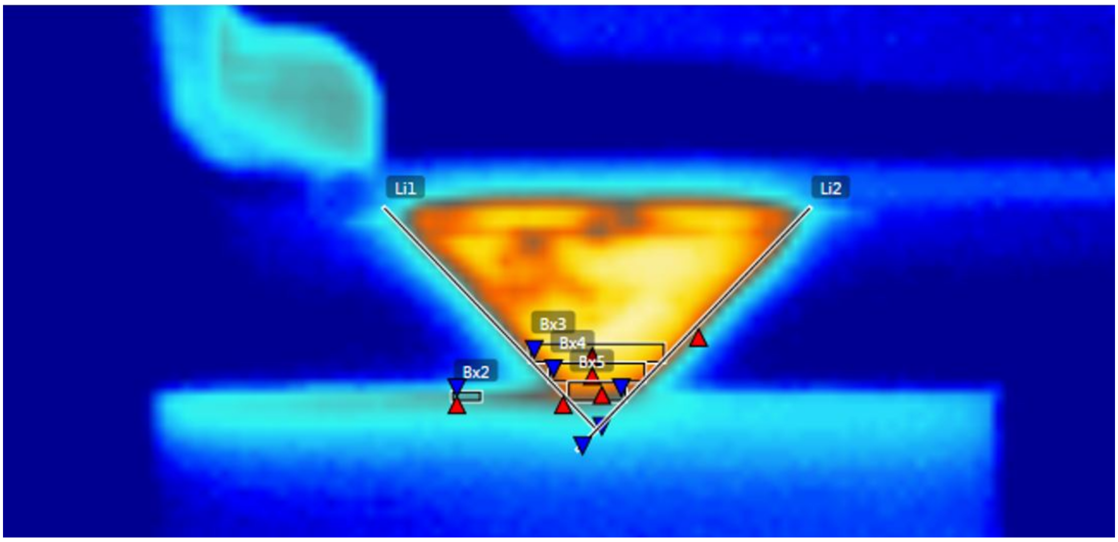


Figure 5.5 *IR image of extruder during print, showing areas in which temperatures were measured*

Table 5.3 *Temperature fluctuations measured during printing*

	Mean °C	**Range °C**
Bx2 - Deposited filament	99.08	4.1
Bx3 - High nozzle	196.87	2.2
Bx4 - Mid nozzle	186.03	2.4
Bx5 - Nozzle Exit	150.92	4.8

5.3.3.2 Relationships between part properties and load

Given the large range of experimentally determined tensile strengths, analysis was carried out to elicit whether there existed any relationship between other part properties and tensile strength. The other part properties explored were cross sectional area at break, part mass and the cross section at break divided by the mass. These were selected as their measurements were found to vary significantly in the test specimens and are properties that can be measured non-destructively. This is important because if a relationship were to be found it would allow the correlation and hence prediction of a part property that would otherwise only be determined through destructive testing.

Scatter plots showing their respective relationships against UTS for the 100% infill samples are given in Figure 5.6. All the relationships can be observed to be stochastic signifying that the UTS cannot be reliably correlated with the considered part properties (cross-sectional area and mass). A similar relationship was observed for the samples with 20% infill.

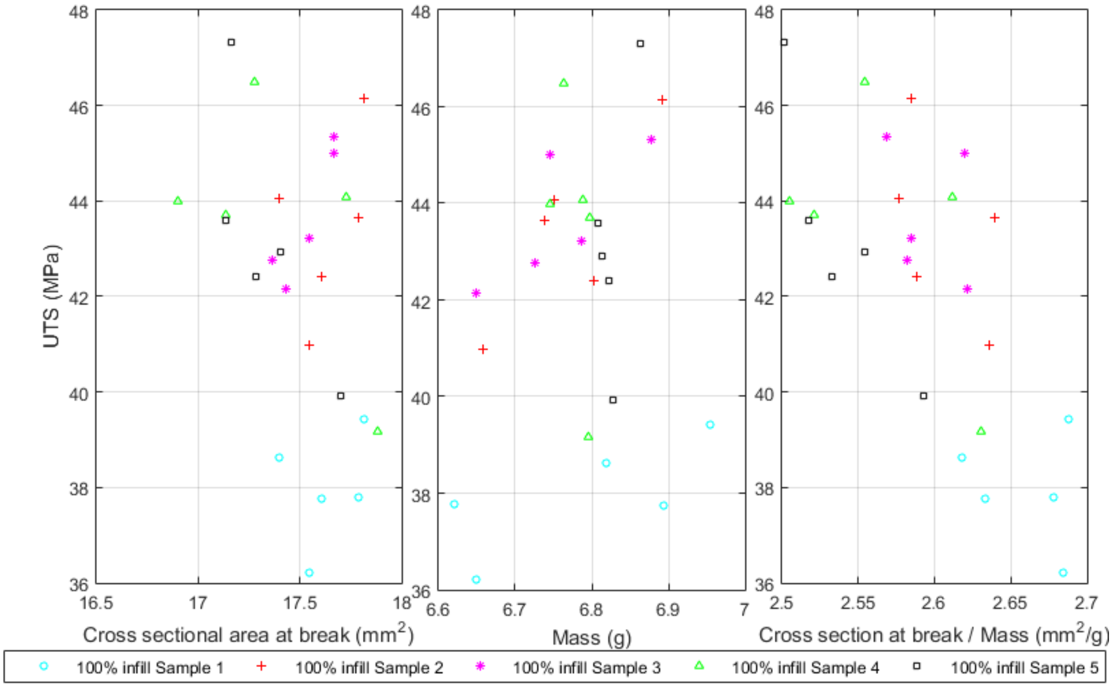


Figure 5.6 *Scatter plots showing stochastic relationship between UTS and other part properties*

5.3.3.3 Applying findings to design tasks

Given the high variability in tensile strengths and that these cannot be correlated to other part properties, a statistical model can be developed to predict the likelihood of a designed part meeting a defined strength requirement. This section highlights how such a model was developed based upon the results of the 100% infill test samples.

A Shapiro-Wilk test for normality [173] was carried out on the break loads and UTSs of all the 100% infill samples. When considered both individually and collectively the sample sets were found to be normally distributed with means and standard deviations as defined in Table 5.1. Probability density functions can then be generated for the 100% infill samples. These are shown in Figure 5.7 for sample UTS. These can be used to predict the likelihood a design will meet a given requirement. It can be noted that one of the curves (Sample 1) is significantly further to the left than the others. We believe that it is attributed to a change in filament roll during the manufacture of the specimens.

A statistical model, such as the one proposed, is a step towards the automation of the design reasoning process as it provides a confidence level that a part manufactured via FDM will have the required mechanical properties.

[173] S. S. Shapiro and M. B. Wilk. *An Analysis of Variance Test for Normality (Complete Samples)*. (1965)

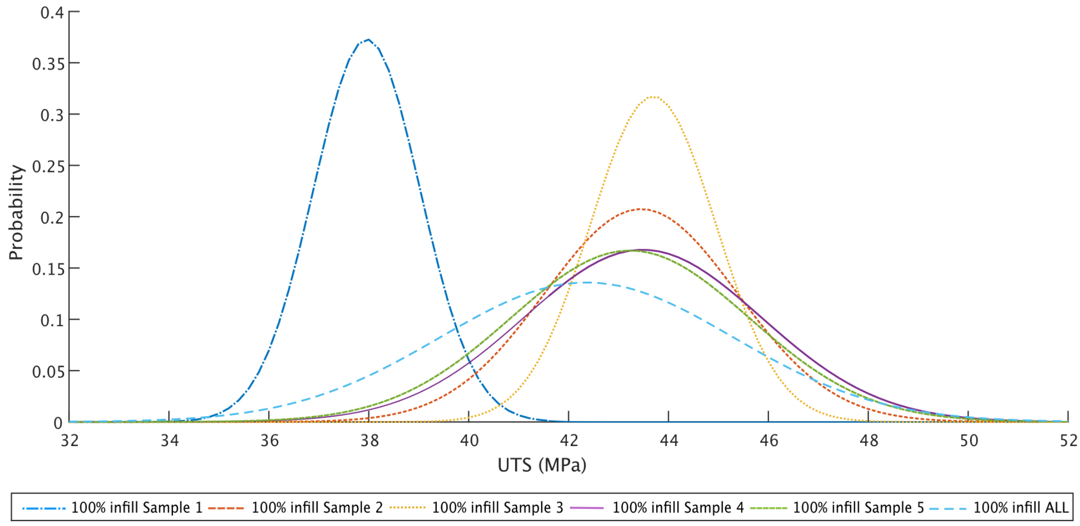


Figure 5.7 *Probability density functions for UTS of 100% infill specimens*

5.3.3.4 Concluding remarks

The section has presented experimental testing results that permit the elucidation of the variability of FDM process. Results suggest that this is caused by extruder temperature fluctuations during manufacture.

The presented statistical models enable the prediction of part properties. These can be directly used to allow the prediction of variety of outcome that can be expected in the manufacture of a part.

5.4 Effect of shape and scale determination

As previously mentioned, it is currently unclear whether the mechanical properties of FDM parts are consistent with respect to shape and scale. The aim of these tests was therefore to elicit the significance of shape and scale on the mechanical properties of parts. To determine the effect of shape tensile tests were carried out on samples with different cross sections but constant area. To determine the effect of scale, tests were carried out on samples with the same cross section but different areas.

Tensile tests were undertaken on an Instron 3343 tensile test machine with loads measured with a 1 kN Instron force transducer. Specimens were extended at a rate of 1mm/min until break.

5.4.1 Method

Six batches of six specimens were manufactured on an Ultimaker 2 with Ultimaker branded silver PLA. All samples were printed with the same reel of filament. An amended test specimen was used for these tests compared to that which for used to deduce the effect of variance. This was to enable a significant variance in cross-sectional shape and area, whilst simultaneously permitting variance of the solid shells printing parameter which can only be varied in discrete increments of nozzle size (0.4mm for the tests carried out).

The first set of specimens concerned with shape all used identical printing parameters, a constant cross sectional areal with rectangular, circular and triangular cross sections respectively (shown in Figure 5.8).

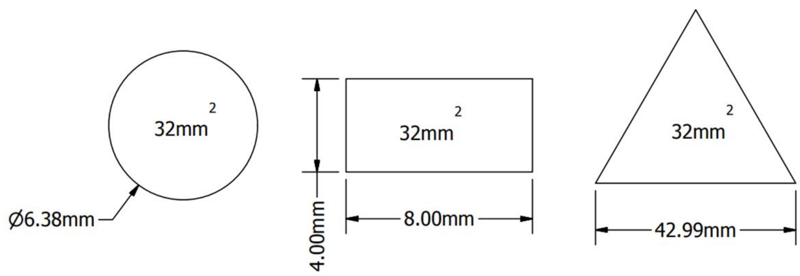


Figure 5.8 *Sample cross sections for determining effect of shape*

The second set used a rectangular cross section of varying area but constant aspect ratio (shown in Figure 5.9). Identical manufacturing parameters were used with the exception of the ½ scaled rectangular cross section which also scaled the solid shells parameter in line with the cross section.

The reduced area section was reduced in length when compared with ASTM specimen in order to ensure break occurred within the length of the extensometer (50mm). A plan of the test specimen is shown in Figure 5.10.

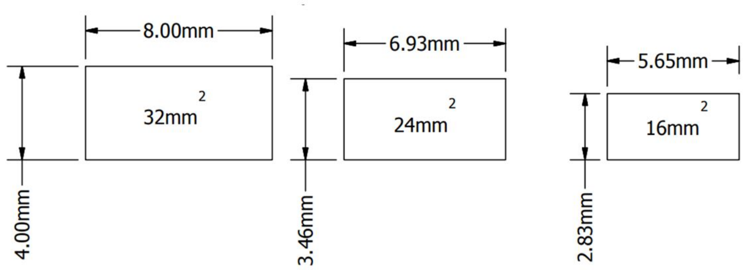


Figure 5.9 *Sample cross sections of tested samples for determining effect of scale*

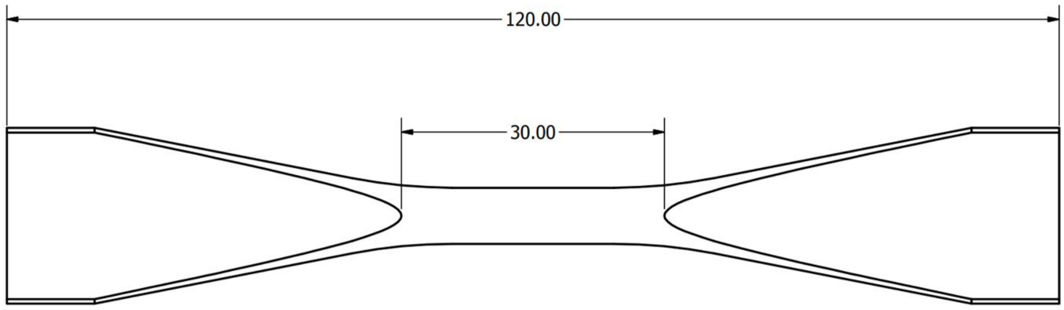


Figure 5.10 *Dimensions of test specimen for shape and scale testing*

5.4.2 Results

Results of the tests carried out to deduce shape and scale are shown in Table 5.4. A moderate variation (9% with respect to UTS) can be observed due to the effect of cross section shape, and a much more significant variation (38% with respect to UTS) can be observed due to the effect of scale. It is noteworthy that maximum break load does not scale linearly with the size of the part.

Table 5.4 *Results of tensile testing to explore effects of shape and scale. Standard Deviation is abbreviated to SD, percentage range is defined as the range divided by the mean expressed as a percentage. Baseline refers to sample 4*

Sample	**1**	**2**	**3**	***4***	**5**	**6**
Scale	¾	½	½	***1***	1	1
Top/Bottom layer thickness & number of solid shells (mm)	0.8	0.4	0.8	***0.8***	0.8	0.8
Cross Section Shape	Rectangle	Rectangle	Rectangle	***Rectangle***	Circle	Triangle
Break Load (N)	800.5	382.9	604.6	***876.4***	906.4	956.7
% difference when compared to baseline	*-9%*	*-56%*	*-31%*	***N/A***	*3%*	*9%*
SD (N)	27.4	7.7	23.5	***29.4***	39.0	37.4
Range (N)	75.3	16.9	65.2	***80.2***	107.9	85.1
% Range	9%	4%	11%	***9%***	12%	9%
Area (mm^2)	24.0	16.0	16.0	***32.0***	32.0	32.0
% difference when compared to baseline	*-25%*	*-50%*	*-50%*	***N/A***	*0%*	*0%*
UTS (MPa)	33.4	23.9	37.8	***27.4***	28.3	29.9
% difference when compared to baseline	*22%*	*-13%*	*38%*	***N/A***	*3%*	*9%*

5.4.3 Discussion

Having identified non-linearity in mechanical performance caused by scale and variance due to cross-sectional shape it is important to identify a possible cause for the variation.

The ratio of solid shells to infill can be observed to have a significant impact on a specimen's tensile properties and can be attributed to the observed non-linearity as the specimens are scaled. It is suggested in existing literature that solid shells contribute more to part strength than infill [174]. Correspondingly, two identical cross-sections with different ratios of infill to solid shell would exhibit different mechanical performance. Table 5.5 demonstrates how the ratio of shell to infill changes as rectangular test specimens are scaled. When maintaining a constant top/bottom layer and solid shells thickness the ratio can be observed to vary from 1.08:1 to 2.21:1

Table 5.5 *Effect of scale on ratio of infill to solid shell*

Sample	**Cross section area (mm^2)**	**Top/Bottom layer & Solid shell thickness (mm)**	**Shell Area (mm^2)**	**Infill Area (mm^2)**	**Ratio shell:infill**	**Break Load (N)**
4	32.0	0.8	16.6	15.4	1.08:1	876.4
1	24.0	0.8	14.1	9.9	1.42:1	800.5
2	16.0	0.4	6.1	9.8	0.62:1	382.9
3	16.0	0.8	11.0	5.0	2.21:1	604.6

When explored as a cause for the observed variation in mechanical performance due to change in cross sectional shape, the ratio of shell to infill cannot be directly identified as a cause. Although the geometric changes do alter the ratio of solid shell to infill as can be seen in Table 5.6 no clear relationship can be observed. A number of other factors could contribute to the differing mechanical performance including part cooling and stress concentrations accelerating failure of the specimens.

5.4.3.1 Concluding remarks

Shape does impact the mechanical performance of the components and causes variation in UTS of 3% and 9%. Effect of scale is significant, especially when the solid shells parameters is scaled with the area. This is likely due to the ratio of solid shell to infill.

[174] M. Goudswaard *et al. Democratising the design of 3D printed functional components through a hybrid virtual-physical design methodology.* (2018)

Table 5.6 *Effect of shape on ratio of infill to solid shell*

Sample	Cross section area (mm^2)	Shape	Shell Area (mm^2)	Infill Area (mm^2)	Ratio shell:infill	Break Load (N)
4	32.0	Rectangle	16.6	15.4	1.08:1	876.4
5	32.0	Circle	18.0	14.03	0.78:1	906.4
6	32.0	Triangle	16.0	15.97	1:1	956.7

5.5 Implications for democratisation of design

The results of this chapter allow the formation of another requirement for a democratising design methodology for FDM and also directs further mechanical testing.

The further requirement for the democratisation of design for FDM is that any methodology needs to account for variability in process and lack of process knowledge. As the process is found to be inherently variable, accurate prediction of part behaviour is unlikely to be possible so physical validation of a part's behaviour is necessary.

Via means of a review of extant process knowledge, the chapter has also demonstrated the size and complexity of the solution space for FDM. This is due to the large number of independently controllable manufacturing parameters, some of which have large and currently unquantified effects on the properties of manufactured parts. A democratising design methodology will therefore need to incorporate a means of managing this knowledge. This represents therefore not a requirement for *what* the democratisation of design needs to do but more a dictator of *how* it should be done.

The ratio of infill to solid shell has been shown to have a significant impact on the mechanical performance of parts. Any simulation strategy implemented to predict part performance must take this into account.

5.6 Concluding remarks

This chapter has characterised the FDM manufacturing process by reviewing extant literature and undertaking mechanical testing to fill identified gaps in knowledge. This has permitted the formation of an additional requirement for the democratisation of design and indicated how this could be achieved.

Chapter 6

Design methodology overview

The previous two chapters have enabled requirements for the democratisation of design to be elicited by characterising the design process for FDM and the manufacturing process itself. When combined with the findings of the literature review, these permit the generation of an appropriate design methodology. This chapter provides a theoretical framework for the design methodology which will later be implemented.

6.1 Four pillars for the democratisation of design

Previous chapters have elucidated the following requirements of a democratising design methodology for FDM. These can now be used to define the pillars of design democratisation for FDM or in other words, the affordances that it must have in order to enable non-technical users to design and manufacture functional parts for themselves. These requirements are re-summarised as follows:

1. **To permit a user to undertake variant design tasks** -The majority of items people would make via FDM are replication, repair or improvement of existing items rather than the creation of new designs [149]. If contextualised with respect to the Pahl and Beitz framework, a democratising design strategy would therefore need to cover the embodiment and detail stages [154].
2. **To make reasoned design decisions on behalf of the user** - The greatest difficulty experienced when designing for FDM is the decision making process (identified in chapter 4). This is in part due to the large and complex FDM design space (identified in Chapter 5) and in depth engineering knowledge required to manufacture functional parts.
3. **To account for variability in process and lack of process knowledge** - There are significant gaps in knowledge of the FDM manufacturing process [175]. This was identified in Chapter 5. This needs to be addressed by incorporating physical testing in order to validate the behaviour of parts.
4. **To permit iterative design** - Results from physical testing need to be incorporated within the design process. To allow this the design process must consist of multiple iterations. This corresponds to the need to ac-

[149] R. Shewbridge *et al. Everyday Making: Identifying Future Uses for 3D Printing in the Home.* (2014)
[154] G. Pahl and W. Beitz. *Engineering Design.* (1984)
[175] Y. Huang *et al. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations.* (2015)

count for variability in the manufacturing process and gaps in process knowledge as were shown in Chapter 5.

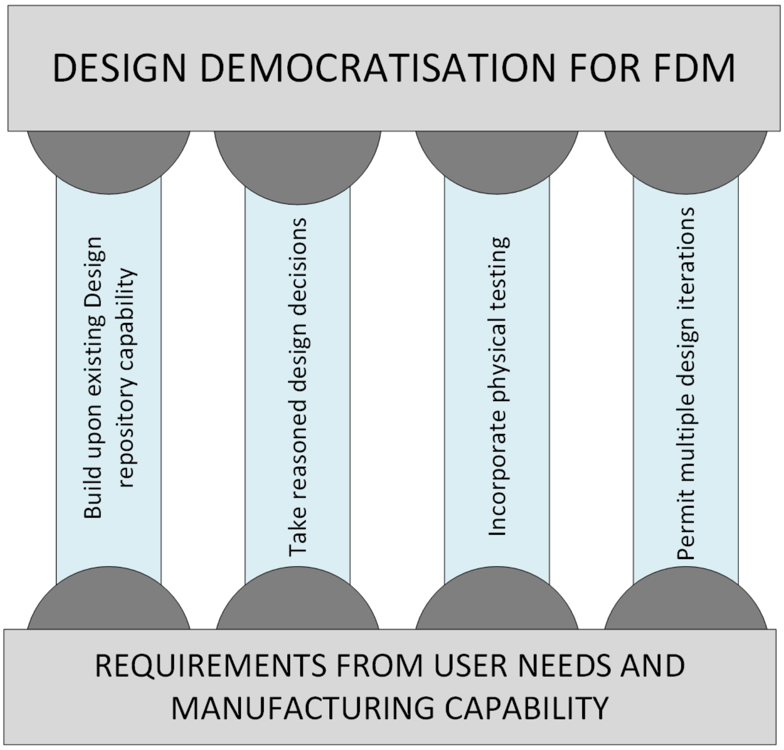


Figure 6.1 *Four pillars of design democratisation*

To meet these requirements, four pillars of design democratisation are defined and are represented in Figure 6.1 These, when incorporated within a design methodology, will enable non technical users to design and manufacture functional components for themselves. The pillars and how they meet the requirements above are defined in Table 6.1. Physical testing can be more broadly considered as functional testing of a component through in its envisaged use-case *not* testing in the sense of determining mechanical properties as carried out in Chapter 5.

The following design methodology is developed incorporating these four pillars in the manners described. Elements of the methodology where these can be found will be identified to highlight where and how they are incorporated.

Table 6.1 *Pillars of design democratisation and validation*

Pillar	Justification
Build upon existing design repository capability	Design repositories are currently widely used providing static CAD models which can be manufactured by home users (as identified in literature review). To enhance their capability the design methodology will incorporate dynamic models which can be specified to an individual user's requirements and available manufacturing capability.
Take reasoned design decisions	The dynamic models will consist of a functional model which permits a simulation of a parts predicted behaviour. This coupled with a capability profile will allow the generation of geometries and manufacturing parameters that enable the automated generation of a satisfactory part.
Incorporate physical testing	Despite the use of functional models and capabilty profiles to simulate a part's behaviour, due to inherent variability in the manufacturing process itself it is necessary to physically validate a part's behaviour. The methodology will therefore incorporate a physical testing element, the results of which can confirm a satisfactory part, or inform the next round of simulation.
Permit multiple design iterations	Because a given design may be unsatisfactory, multiple design iterations must be possible in order to arrive at a satisfactory solution and incorporate physical testing results.

6.2 Methodology overview

The methodology draws upon the affordances of both virtual and physical design domains. Whilst simulation permits quick iteration of designs, it is difficult to make models that behave as the object would in reality. This is particularly true for 3D printing as the effects of many print and printer parameters on the geometric and mechanical properties of manufactured parts are not fully understood and can thus not be reliably modelled.

Manufacturing and physical testing, on the other hand, permits the determination of actual behaviour of the object. It is however more time-consuming and expensive compared to computational simulation. Consequently, the proposed process seeks to combine design libraries with the affordances of both simulation and physical testing into an iterative design process. Simulation is used to reach the best theoretical solution. This can then be manufactured and validated through physical testing. If the design is unsuccessful, these results of can be used to correct the simulation so it better reflects the actual behaviour. This iterative process is continued until part requirements are met.

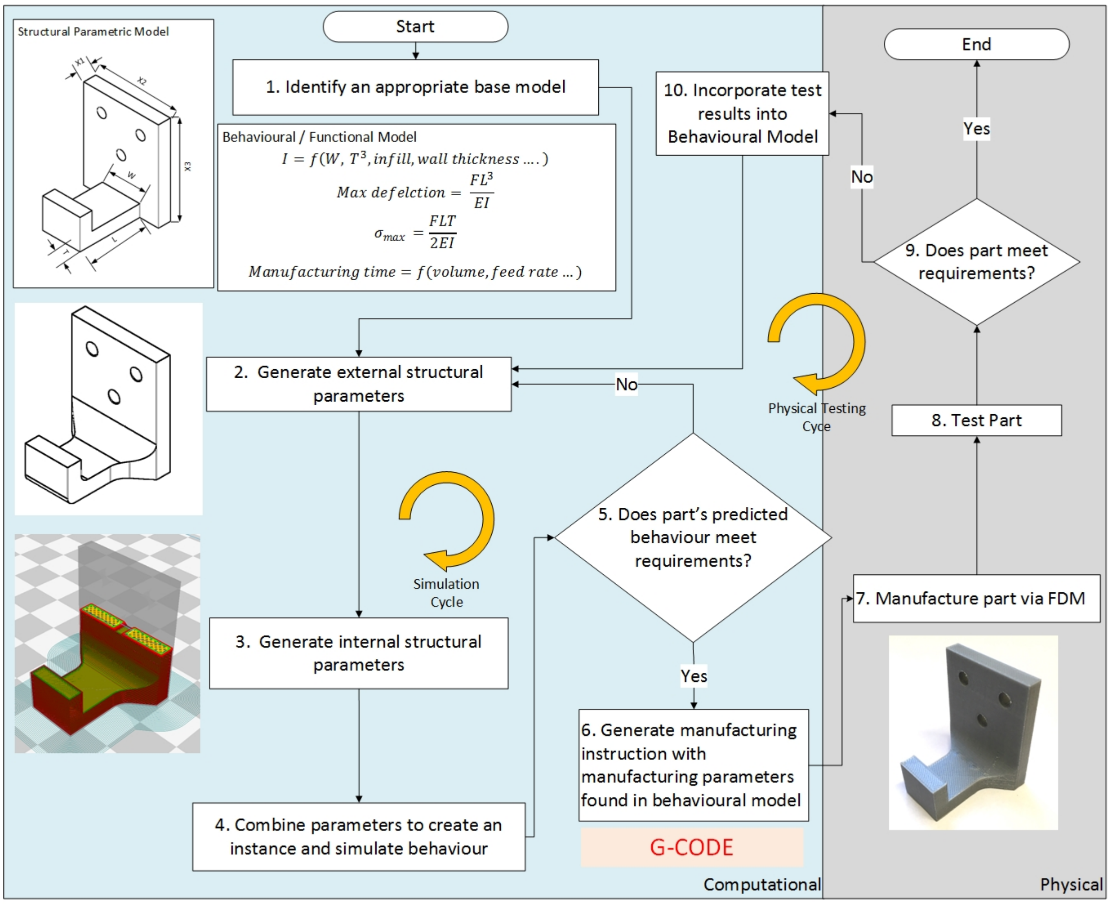


Figure 6.2 *Overview of design method functionality*

A functional diagram of the proposed methodology is shown in Figure 6.2. It consists of 8 main stages which take place in both virtual and physical space. These will be explained in the following section.

The democratising design methodology will be elaborated upon and explored from four different perspectives:

1. **Overview of system architecture in IDEF0 format**.
2. **Functional and structural models, their necessary design representations and roles within the methodogy**.
3. **Presentation of system interaction from the perspective of an individual user**.
4. **Contextualisation of the methodology within the Function Behaviour Structure (FBS) framework**.

At this point it is important to define the class of products that the methodology will be applied to. In Chapter 4, three principle design modes are identified corresponding to fit, size and load. Of these, fit is, at present, beyond the scope of the manufacturing capability and size is widely done already with

FDM. Therefore, the class of products to be manufactured via use of the proposed methodology will look to overcome load as the principle design mode. By addressing this design mode, the target objects represent those that the manufacturing technology is at present capable of producing (consumer/household products). The methodology is therefore developed with the aim of permitting the democratisation of design for functional products that are within the current manufacturing capabilities. The specific requirements that this imposes on the methodology is that it must influence part geometries and manufacturing parameters in order to influence mechanical behaviour.

The envisaged users of the methodology can also be reiterated here. In Chapter 1, the benefits of a distributed manufacturing paradigm underpinned by FDM 3D printing are defined and, although universal benefits are shown, these are considered to be greater in developing countries, provided there exists a level of infrastructure to support these technologies. In addition to this, in Chapter 4, users are defined as being members of generations Y and Z, and as such, are considered to have existing technological familiarity but lack in the practical knowledge necessary to design functional parts. This leads to the methodology needing to provide 'functional' democratisation. A specific user of the methodology can therefore be defined as living in a developing country with suitable infrastructure to support a distributed manufacturing paradigm and a member of generation Y or Z.

6.2.1 IDEF0 representation of system architecture

An IDEF0 representation of the system architecture is shown in Figure 6.3. IDEF0 is used to produce a function model which is a structured representation of the functions of a manufacturing system or environment, and of the information and objects which interrelate those functions [176].

The system architecture defines the design process from after a user has located an appropriate base model from the design library. Block A0 generates instances. Their behaviour is then simulated via use of the functional model and normative capability profile in A1 and the best instance is taken forward for manufacture. The corresponding geometric parameters permit the generation of an STL in block A2. This is taken forward for slicing where it is combined with the manufacturing parameters generated in block A1. The slicing generates a G-code manufacturing instruction which can then be interpreted and realised by the FDM printer (Block 4). The manufactured part is then tested according to the test criteria pre-defined for the model in block A5. The results of this testing determine the next steps. If the manufactured part satisfies the user's requirements the design process is complete. If the part isn't satisfactory, the part's actual and required behaviours are compared in order to gauge the amount of adjustment required in order to direct the search for the next iteration (block A6). The adjustments are then taken to amend either the functional model (block A7) or the capability profile (block A8). In both these cases the normative functional model or capability profile are respectively adjusted so they better represent the behaviour of the part in real life. This cycle is continued until a satisfactory part is manufactured.

Whilst the IDEF0 diagram (Figure 6.3) demonstrates the functional elements of the design methodology, it is also necessary to note some general considerations that for each block which will greatly the methodology's ability to generate a satisfactory solution. These are shown in Table 6.2.

Necessary considerations for each block presented in Figure 6.3 are explored in Table 6.2. These do not constitute an exhaustive list but do provide general factors that must be taken into account when implementing the proposed desisgn methodology.

[176] D. T. Ross *et al. Integrated Computer-Aided Manufacturing (ICAM) Architecture Part II, Volume IV - Function Modeling Manual (IDEF0).* (1981)

Table 6.2 *Necessary considerations to ensure effective implementation of the design methodology for blocks of the IDEF0 diagram (Figure 6.3)*

Block	Necessary considerations
A0	- Prior to instance generation a model that has the potential to be suitable needs to be selected. Checks need to be carried out to confirm that required function is within the scope of the general model selected before next stages of the methodology can be undertaken. - Quality of instance generation is limited by the algorithms used. These need to ensure adequate coverage of the solution space whilst doing so in an acceptable amount of time.
A1	- Simulation of behaviour is greatly dependent upon the quality of functional models and their ability accurately to predict behaviour. - Selection is dependent upon the fitness function used to rank the instances generated. This must enable the generation of a functional part whilst also accounting for the user's and/or AM specific design preferences. - Bounds of solution space with respect to CAM and manufacturing capabilities must be taken into account in order to ensure that it is possible to make the selected design solution.
A2	- Successful completion of this step is underpinned by block A1.
A3	- Successful completion of this step is underpinned by block A1.
A4	- Identification of significant printer errors needs to be carried out at this stage in order to mitigate the risk of confusing design with manufacturing issues as potential causes of functional inadequacies.
A5	- It is essential that the prescribed testing procedure for a given model is within the scope of what can be carried out by an envisaged user with respect to their technical skills and equipment available.
A6	- In order to adequately compare and direct search the actual part behaviour must be directly comparable to predicted behaviour (ensuring dimensional homogeneity). - To direct the search, part requirements are used in order to eliminate particular strategies which could be employed to improve part performance. For example if part size is already at it's upper limit, performance improvement must be achieved through amendment of manufacturing parameters.
A7	- With a single test result this would be carried out by adjusting the expected output of the functional model in accordance with test results. As more results available this could be carried out in a more directed manner. This is commented upon further in section 6.4.
A8	- In order for this to be possible, the independent impacts of each variable must be known. It is likely that adjustments to capability profiles would not be based solely on the results of a single iteration but would take into account results from previous tests. This is commented upon further in section 6.4.

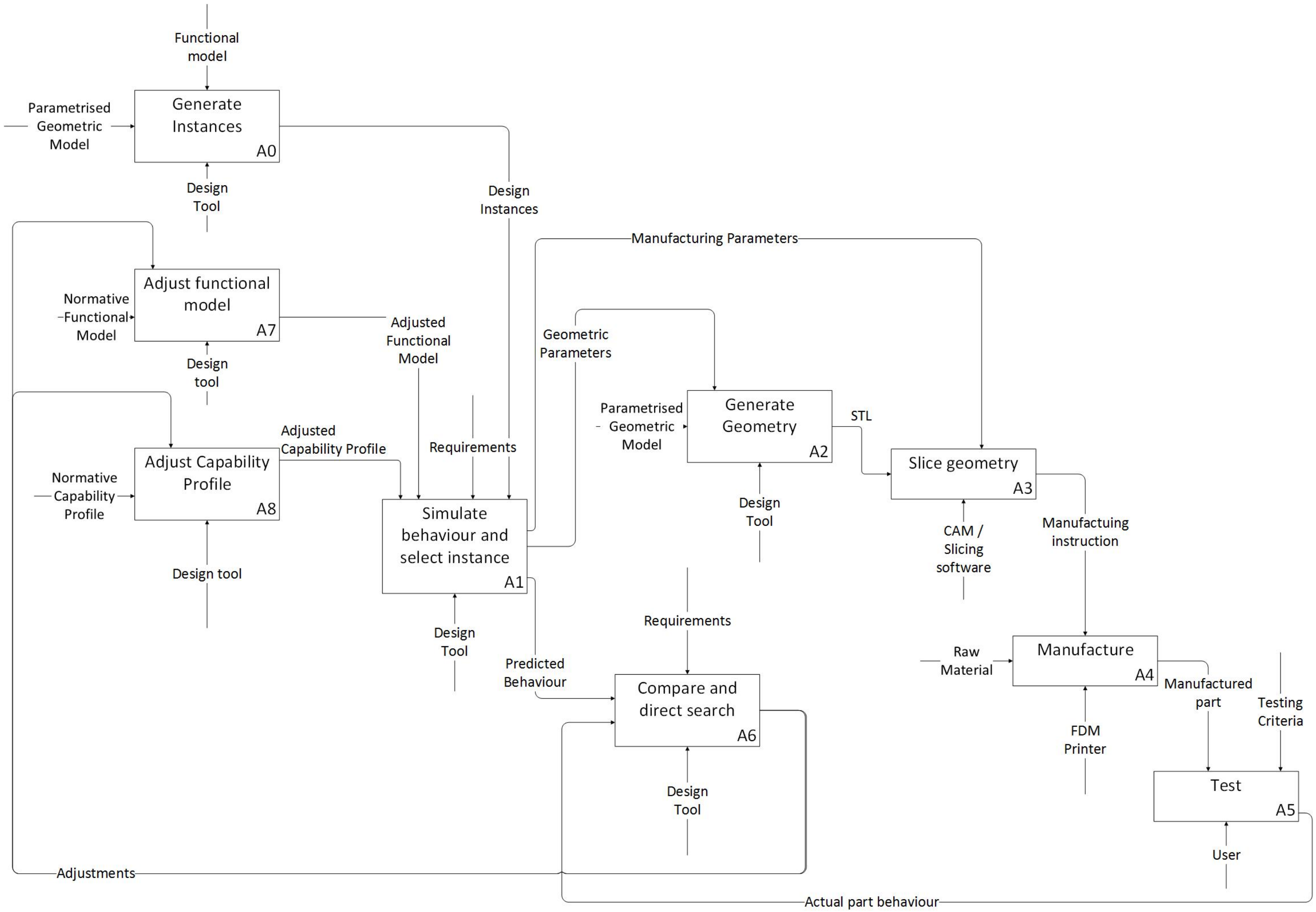


Figure 6.3 *IDEF0 representation of system architecture*

6.2.2 Functional and structural models

The dynamic models hosted within the design library consist of functional and parametric structural elements. These work to vary geometric and manufacturing parameters that can meet functional requirements. The function of these is enabled by an FDM capability profile. Figure 6.4 demonstrates the different model types, their roles and how they interact with each other.

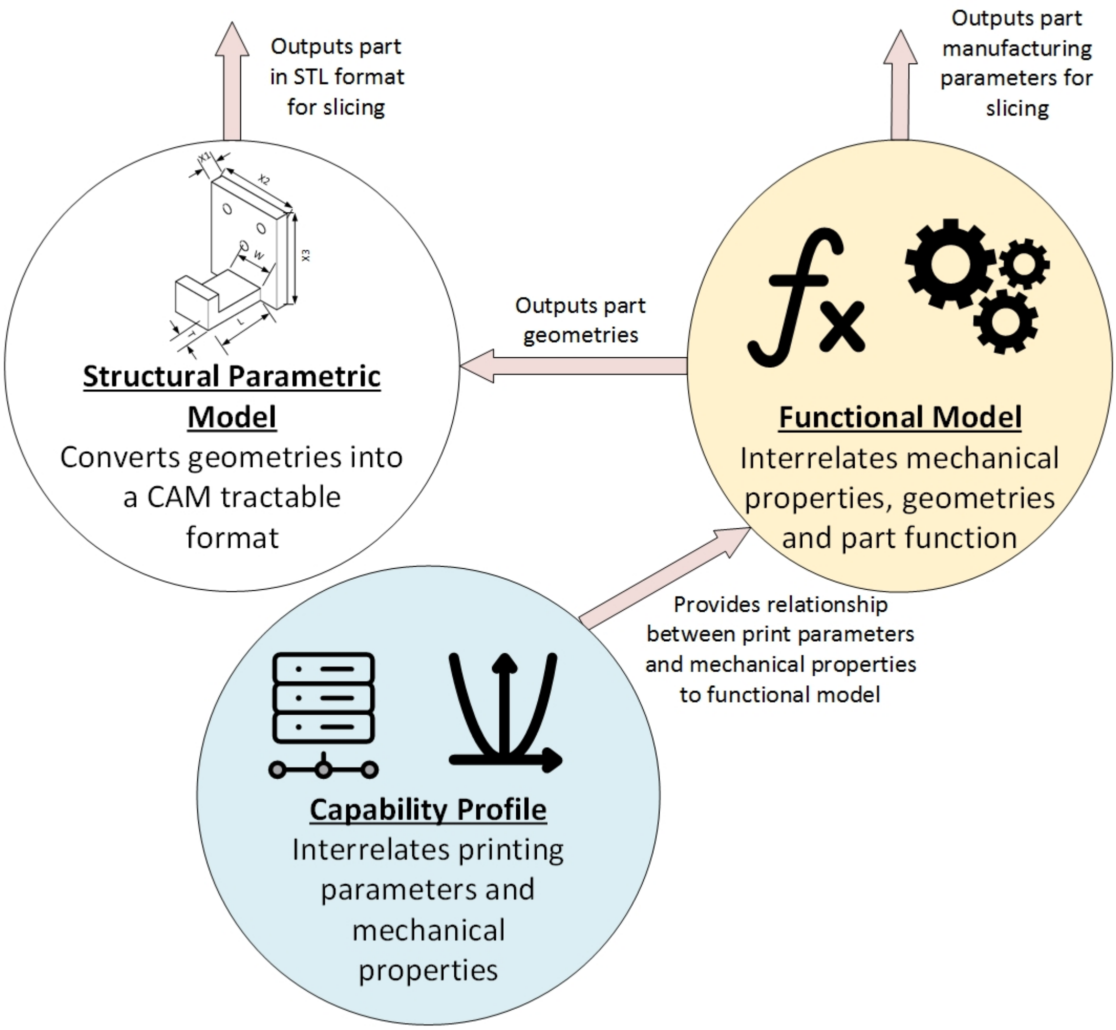


Figure 6.4 *Model types within the methodology and how they interrelate*

The roles of these respective models are as follows:

- **Capability Profile** - to relate and convert print parameters to mechanical properties.
- **Functional Model** - to convert mechanical properties and geometry into part function.
- **Structural Parametric Model** - convert geometric parameters into a CAM tractable STL which can then be used in slicing software.

Interactions between the functional model, structural parametric model and capability profile will all be fully automated. The outputs of the model (STL and manufacturing parameters) will be taken by the user and input into their slicing software.

Whilst these dynamic models are envisaged to be used by non-technical users, the making of them will need to be undertaken by experts. This will be considered in greater detail in the discussion chapter.

6.2.3 User interaction

The methodology's ability to democratise design can be demonstrated by the reduction in activities that a user must undertake. A flow chart of user interaction is shown in Figure 6.5. Requirements to make reasoned designed decisions have been removed. It is only necessary for the user to select their required base model, input their requirements, print the part, test to see if it is satisfactory, and, in the event that it is not, input the test results so a better part can be generated.

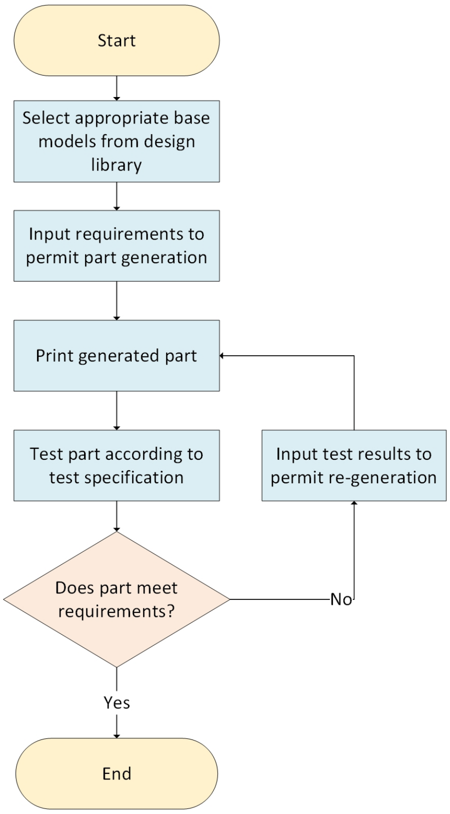


Figure 6.5 *Use of design methodology from perspective of user*

In order to identify how the democratisation of design has been achieved it is necessary to the assess if and how the difficulty of a user's interaction is reduced. To do this, the method used in the characterisation of the design process in Chapter 4 was used to log the envisaged steps that a user would take in the design of a load bearing hook. From this, a heat map can be used to identify the difficulty experienced and permits a comparison with a normal CAD based process. This heat map is shown in Figure 6.6. It shows that the in total *Ability* is reduced by 0.7 points and *Understanding* is reduced by 1.8 points. A requirement for the democratisation of design was identified as removing the need to take reasoned design decisions. This is achieved by the methodology as respective decreases can be seen in Decision making. *Ability* is reduced by 3.0 points and *Understanding* is reduced by 1.6 points. This has been achieved, it appears, by removing the users need to generate or amend geometry according to specific functional requirements. This is shown as the Sample Hook Democratised presents a difficulty score of zero for *Ability* and *Understanding* in all iterations for geometry amendments.

A trade-off can be observed with slight increased difficulty in software interactions and in observations and measurement. This is likely due to a shift from geometry related amendments to other software decisions and is to be expected. The additional observation and measurement difficulty comes from the need to have a rough understanding of a part's requirements before beginning the generative cycles. In spite of the slight increase, it can be determined to be an acceptable level given the magnitude of the decrease seen in the area of decision making.

Figure 6.6 represents the predicted performance of the design methodology with respect to its ability to enable the democratisation of design. In the implementation which take place in Chapter 8, a similar heat map will be generated to compare the actual difficulty experienced by a user of the methodology to what was predicted.

		Software Interaction		Hardware Interaction		Observation & measurement		Decision		Geometry		TOTAL	
		A	U	A	U	A	U	A	U	A	U	A	U
Hook	Iteration 1	1.7	0.0	2.0	0.0	1.5	3.0	3.0	3.2	2.5	0.0	2.2	3.2
	Iteration 2	1.8	0.0	2.0	0.0	1.5	2.5	3.0	3.6	1.5	0.0	1.8	3.3
	Iteration 3	1.8	3.0	2.0	0.0	2.0	3.0	3.0	3.3	2.5	3.0	2.1	3.2
	Design Total	1.7	3.0	2.0	0.0	1.7	2.9	3.0	3.3	2.3	3.0	2.1	3.2
Sample Hook democratised	Iteration 1	1.3	1.3	1.0	0.0	1.5	1.0	0.0	1.6	0.0	0.0	1.3	1.4
	Iteration 2	1.5	1.3	1.0	0.0	2.0	1.0	0.0	2.0	0.0	0.0	1.5	1.4
	Iteration 3	1.5	1.3	1.0	0.0	2.0	1.0	0.0	2.0	0.0	0.0	1.5	1.4
	Design Total	1.4	1.3	1.0	0.0	1.8	1.0	0.0	1.7	0.0	0.0	1.4	1.4
Diiference	Iteration 1	-0.4	1.3	-1.0	0.0	0.0	-2.0	-3.0	-1.6	-2.5	0.0	-0.9	-1.8
	Iteration 2	-0.3	1.3	-1.0	0.0	0.5	-1.5	-3.0	-1.6	-1.5	0.0	-0.3	-1.9
	Iteration 3	-0.3	-1.7	-1.0	0.0	0.0	-2.0	-3.0	-1.3	-2.5	-3.0	-0.6	-1.8
	Design Total	-0.3	-1.7	-1.0	0.0	0.1	-1.9	-3.0	-1.6	-2.3	-3.0	-0.7	-1.8

Figure 6.6 *Difficulty comparison with case study from characterisation of FDM design process*

6.2.4 Contextualisation within an FBS framework

The presented design methodology can be loosely related to a two tier FBS approach. One computational tier, the other physical. The Function Behaviour Structure (FBS) framework [58] states how a product is designed with respect to the relationship of an items function (what it does), its behaviour (how it does it) and its structure.

The presented method can be likened to a two tier FBS approach that spans both virtual and physical spaces. The functional element is not considered as the design method is only concerned with variant design. As such the part's function is predetermined. An amended FBS representation is shown in Figure 6.7.

The steps as shown in the diagram are defined in Table 6.3.

In virtual or computational space, the simulated structure is amended to meet the simulated behaviour. And then once manufactured - translated to the physical space - this simulated behaviour is compared with the actual behaviour. The comparison therefore of the simulated, expected and actual behaviours drives the design of a successful instance and also the evolution of the generative model itself so in future it can better adapt to specific requirements. These comparisons are demonstrated in Figure 6.7 and are represented by comparisons 1, 5, 9 and 10.

[58] J. S. Gero and U. Kannengiesser. *The situated function-behaviour-structure framework*. (2004)

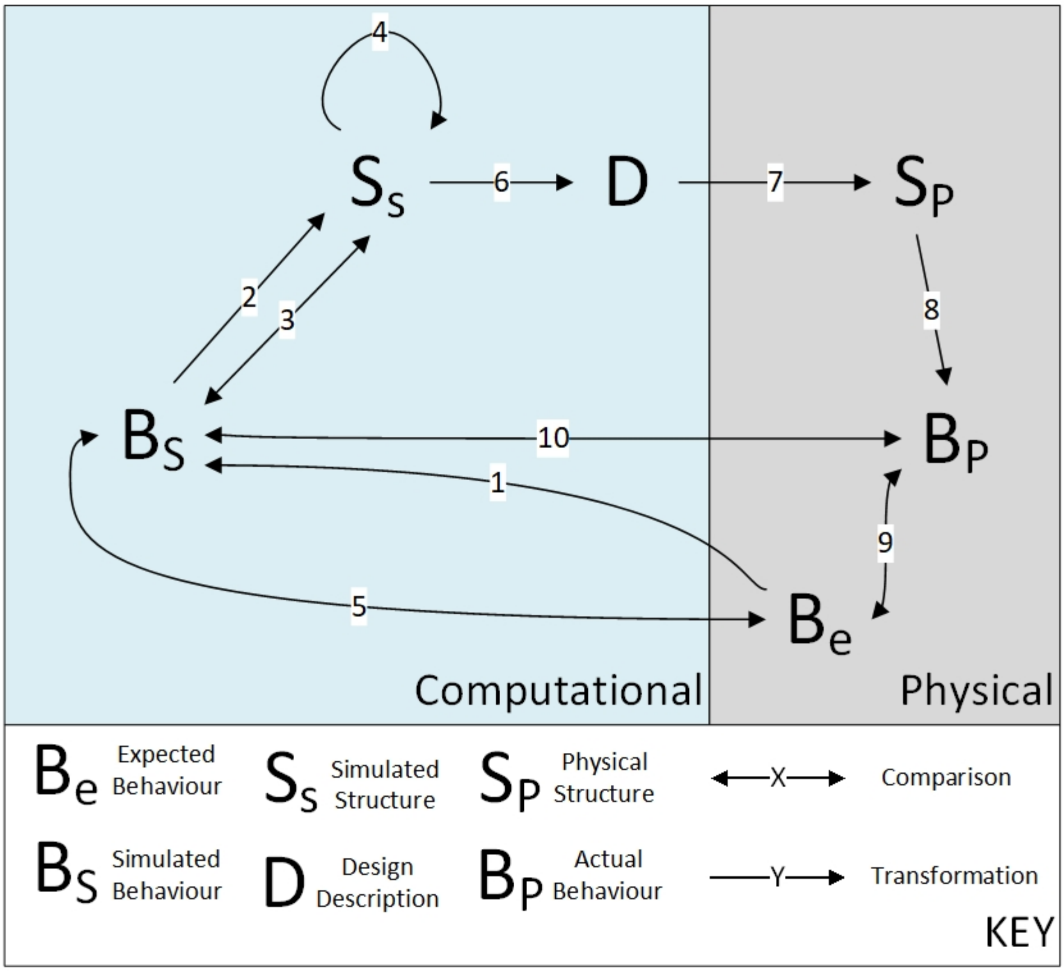


Figure 6.7 *Design methodology represented as a two tier FBS framework*

Table 6.3 *Design methodology contextualised into FBS framework. References to blocks correspond to those defined in the IDEF0 representation of system architecture shown in Figure 6.3*

Process	**FBS Step**	**Process within design methodology**
1	Formulation - expected behaviour in the Physical domain is transformed into simulated behaviour in the computational domain	Interpretation of requirements by functional model
2	Synthesis - the simulated behaviour is transformed into a solution structure	Generation of CAD model and possible manufacturing parameters within FDM design space (Block A0)
3	Analysis - derives simulated behaviour of structure	Elucidation of the predicted behaviour of the CAD structure (Block A1)
4	Reformulation of design structure	Amendment and re-generation of CAD structure if it is unable to meet requirements (Block A0)
5	Evaluation to compare the behaviour derived from structure with expected behaviour to decide if design is able to meet requirements	Compare generated solution with requirements (Block A1)
6	Documentation or production of design description	Conversion of CAD model into G-Code instruction (Blocks A2 & A3)
7	Reification - design is transferred from computational to physical space	FDM printing of design (Block A4)
8	Analysis 2 - determination of actual behaviour	The physical testing of the object permits the elucidation of actual part behaviour (block A5)
9	Evaluation 2 - comparison of expected and actual behaviour	Determination of whether part can perform satisfactorily (Block A6)
10	Evaluation 3 - comparison of simulated and actual behaviour	In the event of an unsuccessful design, the comparison of these behaviours directs the search in the next design iteration (Block A6)

6.3 Underpinning technologies

The function of the methodology is underpinned by two main tools. Whilst these will be elaborated upon in greater detail in subsequent chapters they will be briefly commented upon here in order to provide an overview of how the design methodology will function once implemented.

6.3.1 Capability Profile for FDM

Design reasoning capability is enabled by an FDM capability profile. This provides a foundation upon which design decisions can be made. In Chapter 5 the FDM manufacturing process was characterised and in doing this, the general impact of manufacturing parameters on the behaviour of finished parts was elucidated. It is therefore possible to draw these together to define the parameters that need to be included within an FDM capability profile. This will then enable the manufacturing parameters to be directly converted into mechanical properties.

It was previously recognised that is necessary to undertake testing on an individual printer in order to usefully determine FDM manufacturing capability in a generalisable and useful manner. Chapter 8 details the creation of a capability profile for a printer.

6.3.2 Defining and exploring the solution space

Definition and navigation of the FDM solution space is essential in generating functioning parts. Metaheuristic optimisation methods will be assessed with respect to their ability generate solutions and find geometric and FDM manufacturing parameters that would yield functional parts. These are Evolutionary Algorithms (EAs), Particle Swarm Optimisation (PSO) and Simulated Annealing (SA). This is detailed in the Chapter 7.

6.3.3 Physical testing and incorporation of results

The Third Pillar of design democratisation for FDM is that physical testing must be incorporated in order to account for the inherent variability in the manufacturing process. The testing itself would be unique for each set of dynamic models and would be defined by the expert designer that generates it. The general requirements of these would be that:

- They are integrable with an appropriate fitness function for a metaheurstic search strategy used to navigate the FDM solution space.

- They are of an appropriate low difficulty level to be used by a non-expert designer.

There are then two main ways in which the results of physical testing can be incorporated into design iterations - through refinement of either the capability profile or the functional model so the virtual representation of the object better mirrors its real behaviour.

The particularities of achieving this are explored through means of a case study in the Implementation Chapter.

6.4 Iterative hierarchy

The presented methodology and the incorporated element of physical testing presents a number of opportunities for design learning that follow Confuscius' three methods of acquiring wisdom [177] which are defined as follows:

- **By experience** - the *bitterest*.
- **By imitation** - the *easiest*.
- **By reflection** - the *noblest*.

On initial use of the design methodology, due to a relatively limited amount of process knowledge, users will likely need to engage in a large number of virtual-physical iterations in order to arrive at a suitable part. This represents learning via direct experience and will therefore be the slowest and arguably bitterest form of learning. This is the learning process carried out by the system on an individual use basis.

After a number of identical parts are manufactured by different users, process knowledge grows and lessons learned from the different design cycles are able to inform the decisions taken for the next design of the same part. In this way, when a different user wishes to make the same part, through imitation (i.e. use of existing knowledge) their design experience can be quicker and easier. This is the type of learning taking place by groups of users generating designs for the same item.

This accumulated design knowledge can also be applied to different design tasks. Elements of that which is learned in the design of part A can be applied to parts B & C. This can be viewed as learning by reflection as knowledge is transferred across domains to permit the design or different parts. This is the global learning undertaken across all designs using the design methodology. The ascertained

[177] Confucius. *The Analects.* (1979)

knowledge can be pooled to make evermore effective models of the FDM process and refine the dynamic models themselves.

In literature, a similar concept exists as Communities of Practice. These are defined as ‘groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly’ [178] and their purpose is to ‘develop members’ capabilities; to build and exchange knowledge’ [179]. In the context of design for additive manufacturing, the global design learning afforded by the wider implementation of the design methodology enables a community of practice, with users learning from each others design experiences.

Whilst wider implementation would achieve learning by imitation and reflection, they are outside the scope of the work undertaken within this thesis. The work covered in the subsequent chapters will all be working towards learning by experience for an individual user of the system. Whilst unfortunately Confuscius’ bitterest mode of acquiring wisdom, it lies at the beginning of the methodology which, statistically speaking, is a good place to start.

6.5 Conclusion

This chapter has presented a design methodology built upon the four pillars of design democratisation that were deduced from the identified requirements in previous chapters.

The methodology was presented at a system level, from a functional perspective and also from an envisaged user’s perspective. The overall functionality of the methodology was presented as an IDEF0 representation of the system architecture. The functionality and interactions of the functional and structural models were defined in order to elicit the way in which these work together to permit the generation of functional parts. The methodology was also covered from a user’s perspective in order to show how the system would be interacted with and also to demonstrate the steps that are removed from the designer.

The formation of a capability profile for FDM in order to capture necessary knowledge of the manufacturing process is defined. This in conjunction with a functional model is used to define the space in which an appropriate solution can be found. To explore this solution space, metaheuristic search strategies

[178] E. Wenger. *Communities of practice a brief introduction.* (2011)
[179] E. Wenger and W. Snyder. *Communities of Practice: The Organizational Frontier.* (2000)

are compared and contrasted and the best presented for use within the design methodology.

The discussion explores the iterative learning hierarchies embedded within the design strategy and how these align with Confuscius' methods of acquiring wisdom. Whilst imitation, reflection and experience are all covered by the methodology, only the latter lies within the scope of the thesis.

Having presented the design methodology from a number of different perspectives, the next chapters will detail the implementation of this methodology. First, an implementation of the methodology will be presented in order to define an appropriate tool-set and means of navigating the solution space. Following this, experimental work will be detailed to permit the instantiation of a capability profile, then the methodology will be fully implemented for a number of case studies.

Chapter 7

Verification

Chapter 6 presented a platform agnostic design methodology able to facilitate the democratisation of design. This chapter presents a first instantiation of the methodology in order to verify the use of the tools that are used in order to implement it. The instantiation is simplified and used to assess the suitability of the tools selected and also enables the specification of an appropriate means of navigating the solution space which is necessary for the generation of functional parts.

First the tool-set used in the implementation of the design methodology is presented, followed by an instantiation that illustrates its use. This instantiation is then employed to assess the performance of different meta-heuristic algorithms in navigating the solution space and generating solutions.

7.1 Implementation tool-set

To realise the design methodology presented in Chapter 6, structural and manufacturing parameters need to be generated based upon predicted behaviour from functional models. As such, a platform that could permit both these elements was sought. To achieve this, a suitable platform would need to meet the following requirements by enabling:

- Functional modelling of how the part will behave by concomitantly incorporating both geometric and manufacturing parameters.
- A means to navigate the solution space and evaluate which generated solution is best.
- The incorporation of an FDM capability profile.

A number of tools were considered. Implementation could be done from scratch in a scripting program such as Matlab or Python. Although employing an approach such as these would enable flexibility in implementation, these options were decided against so as to avoid re-inventing the wheel and creating functionality already featured in existing CAD platforms.

Parametric modelling is widespread and features in a number of CAD tools. These include Solidworks, Catia and FreeCAD [180]. Integrated scripting capability is essential in permitting both functional modelling and the incorporation of a capability profile. This capability was only found to feature in Rhino 6, in particular within its Grasshopper parametric design add-on. Because of this, it was selected as the tool-set for implementing the design methodology. The following section explores the functionality of this tool in greater depth.

[180] L. Gaget. *Sculpteo: Parametric Modelling Software*. 2018

7.1.1 Rhino 6 & Grasshopper

Rhinoceros geometry is a NURBS based CAD platform [181]. Whilst being a capable platform in itself, it was selected principally for its Grasshopper add-on [182] which is 'for designers who are exploring new shapes using generative algorithms. Grasshopper is a graphical algorithm editor tightly integrated with Rhino's 3-D modeling tools' [183].

It was initially developed as a means of allowing users to automate tasks through visual descriptions between entities without the need to write code [184] [185]. A user is able to drag and drop blocks onto the grasshopper canvas. With these, geometries can be created. This is similar to a typical hierarchical constructive solid geometry tree displayed in CAD systems, the difference being that rather than it being implicit (in that it is generated to describe geometry that is created), it is explicit in that it defines the creation of geometry. The Grassopper canvas is shown in Figure 7.1. Grasshopper also has a number of features that enable the generation of functional models which is essential for implementing the design methodology presented in Chapter 6. These are as follows:

- **Python scripting capability** - Permits the generation of custom code which will be essential in the incorporation of capability profiles, generation of functional models and definition of fitness functions.
- **Shape information** - Geometry created in Rhino or Grasshopper can be analysed and properties such as second moment of area easily exported. Such properties are necessary in the generation of functional models.
- **Built in solvers** - Grasshopper features a number of built-in solvers. These include a deterministic solver as well as metaheuristic solvers. These will be necessary for automated exploration of the solution space.

Existing applications of Grasshopper in design for additive manufacture include the generation of dashboards for visualising the AM solution space in order to permit users to select the best design from a suite of generative designs [186].

Having defined the tools used in implementing the design methodology, a use case will now be presented to verify the suitability of their application.

[181] Robert McNeel & Associates. *Rhino 6 Overview.* 2018
[182] Robert McNeel & Associates. *Grasshopper.* 2019
[183] D. Rutten. *Grasshopper 3D.* 2019
[184] A. Webb. *Origins of Grasshopper.* 2013
[185] G. Celani and C. Eduardo Verzola Vaz. *CAD scripting and visual programming languages for implementing computational design concepts: A comparison from a pedagogical point of view.* (2012)
[186] S. Goguelin *et al. A Data Visualization Dashboard for Exploring the Additive Manufacturing Solution Space.* (2017)

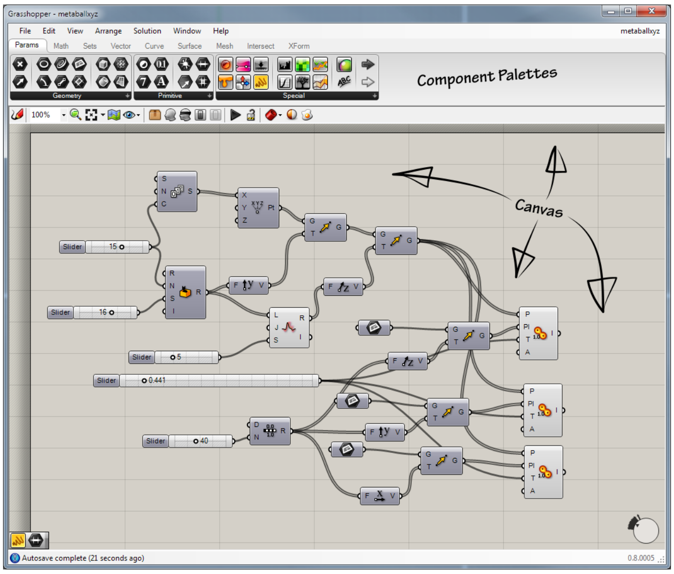


Figure 7.1 *Grasshopper canvas (From [187], licensed under creative commons).*

7.2 The Universal Hook Generator (UHGen)

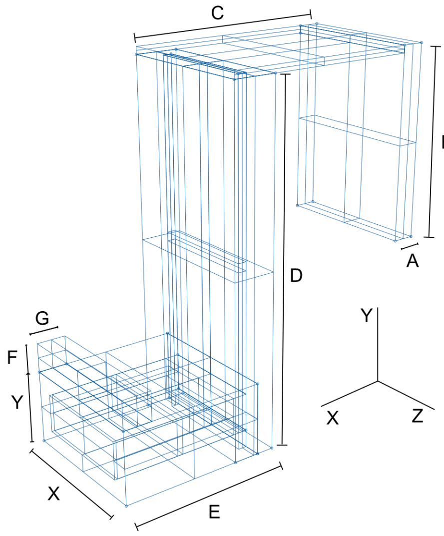
In order to illustrate the design methodology, the first case considered is that of the Universal Hook Generator (UHGen). This consists of functional and parametrised geometric models which would both be held in a design repository. The various dimensions of the parametrised geometric model are shown in Figure 7.2a. Dimensions can be modified to allow the hook to fit over a door whilst being able to hold a load of a specific magnitude. The functional model permits the generation of geometries and manufacturing parameters that permit the hook to hold a given load defined by the user. A bending load case is used to define its behaviour with a load being applied at the end of the hook. The functional model in this instantiation is defined as Equation (7.1). It describes the hook's behaviour in bending as a function of manufacturing and geometric parameters.

$$F_{MaxBend} = \frac{UTS.I_{XXShell}}{y_{shell}.d} + \frac{UTS_{infill}.Infill.I_{XXInfill}}{y_{infill}.d} \tag{7.1}$$

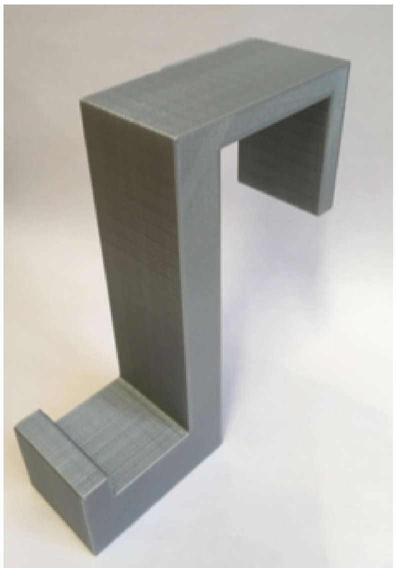
Where $F_{MaxBend}$ is maximum load under bending, UTS is ultimate tensile strength, I_{xx} is the second moment of area about X axis, y is the distance to the neutral axis and d is the distance of applied load to the pivot. Subscripts denote whether a variable corresponds to the shell or infill.

Equation (7.2) is a simplified capability profile, defining UTS as a function of layer height. It is based on extant testing results in literature. Whilst it is accepted that these are not generalisable [188] it allows the testing of the system

[188] D. Popescu *et al. FDM process parameters influence over the mechanical properties of*



(a) *Parametrised Hook, axes correspond to printer axes.*



(b) *Printed Hook*

Figure 7.2 *Parametrised and printed hooks*

architecture before a full capability profile is generated.

$$UTS = UTS_{nominal} + 23MPa.mm^{-1}(Layerheight - 0.3) \tag{7.2}$$

The fitness function is then defined according to Equation (9.6). It seeks to maximise the bending load, whilst minimising material usage. Two penalty factors can be applied if the infill is less than or equal to 20% (so would produce a poor-quality print) or it does not meet the defined load requirement. The required load in this instantiation is 400N.

$$Fitness = C_1.C_2.\frac{Load}{Area_{CrossSection}} \tag{7.3}$$

where $C_1 = 0.1$ if$F_{max} < F_{required}$, else $C_1 = 1$, $C_2 = 0.1$ if $Infill \leq 0.2$ else $C_2 = 1$ and $Load = Min(F_{MaxBend}, F_{required})$.

The use of the Equation (7.1), Equation (7.2) and Equation (9.6) account for both external part dimensions and the manufacturing parameters that impact a part's mechanical properties. The following table (Table 7.1) shows the parameters that are included and can therefore be varied. It also details upper and lower bounds, as well as allowable increments for each.

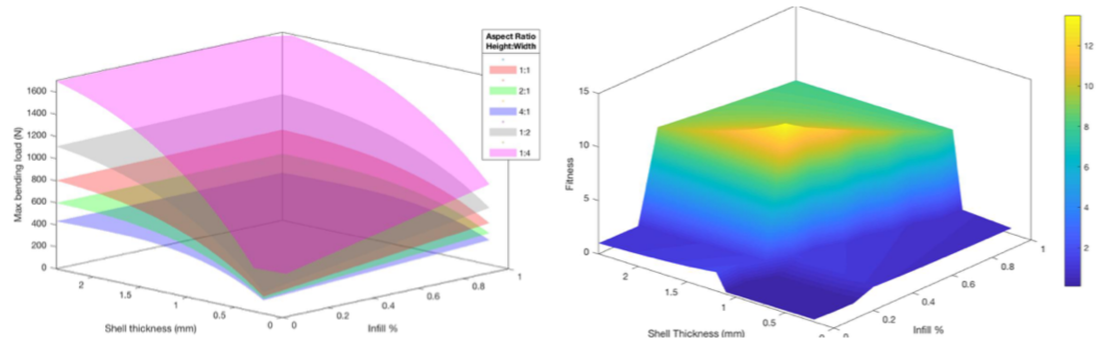
Figure 7.3a shows the relationship between load with respect to aspect ratio, infill % and shell thickness for a constant cross-sectional area (height x width) of

polymer specimens: A review. (2018)

Table 7.1 *Search space parameters*

Parameter	Lower, upper & increment
Height	Min: 5mm, Max: 40mm, Increment: 0.1mm
Width	Min: 5mm, Max: 40mm, Increment: 0.1mm
Layer Height	Min: 0.04mm, Max 0.3mm, Increment: 0.01mm
Infill Percentage	Min: 0%, Max: 100%, Increment: 10%
Top / Bottom Layers	Min: 1, Max: 10, Increment: Layer height
Solid Shells	Min: 1, Max: 10, Increment: Nozzle width

$100mm^2$. It demonstrates the effect that the infill percentage and shell thickness have on maximum load. Figure 7.3b shows the objective function with respect to shell thickness and infill % for an aspect ratio of 2:1 (height to width). A clear global maximum can be observed. Mapping the solution space demonstrates that the solution space is non-trivial whilst also permitting visualisation of the effect that penalty factors have on it.



(a) *Max bending load for a hook of constant cross section of 100mm^2*

(b) *2:1 aspect ratio hook solution space with respect to fitness function*

Figure 7.3 *Parametrised and printed hooks*

7.3 Generating Solutions

Having defined the problem, it is necessary to classify it in order to determine an appropriate means of solving it. The design problem being solved can be classified as difficult as it corresponds to two of the five reasons for which a problem can be difficult [189]. Firstly, an exhaustive search for the best answer is not possible due to the large number of search solutions (3.6x10^9). Secondly, due to the intended outcome of the design method being to enable non-technical users to design functional parts, it cannot be assumed that the person solving the

[189] Z. Michalewicz and D. B. Fogel. *How to Solve It : Modern Heuristics.* (2004)

problem will possess the knowledge necessary to find an appropriate solution. In addition to this, in complex problems, instead of a single solution, a number of different solutions could be optimal. This yields deterministic approaches ineffective as they cannot provide different feasible solutions as they consistently yield the same result. Gradient methods too can be ineffective as they are ill-defined for non-differentiable functions and may not be suited to non-linear or discontinuous objective functions that typically define engineering optimisation problems [190], of which the design problem considered for this instantiation is no exception. Many of the parameters included have non-linear effects on the part's mechanical behavior. As such, Grasshopper's built in deterministic solver (Goat) was unable to generate a solution due to the complexity of the solution space.

Metaheuristics can be broadly defined as 'high level strategies for exploring search spaces by using different methods' [191]. They can be applied to 'almost any kind of optimization problem, regardless of the type (e.g. continuous/discrete, linear/nonlinear, convex/nonconvex) and number of variables' [192]. Because of their wide-ranging applications, three metaheuristic optimisation methods have been chosen to assess their ability to find geometric and FDM manufacturing parameters that would yield functional parts. These are Evolutionary Algorithms (EAs), Particle Swarm Optimisation (PSO) and Simulated Annealing (SA).

SA uses equations that describe metallic annealing and applies them to explore the solution space [193]. The algorithm identifies areas of high fitness values and then fine tunes its position within this region [194]. PSO uses a randomly initialised set of particles that move through the solution space with a velocity defined by the best experience of its own and the population. This drives the swarm towards the point with the highest fitness value [195]. EAs 'apply the biological principles of mutation selection and inheritance' [194]. They populate the solution space and this population is selectively culled and recombined

[190] M. Wetter and E. Polak. *A CONVERGENT OPTIMIZATION METHOD USING PATTERN SEARCH ALGORITHMS WITH ADAPTIVE PRECISION SIMULATION Environmental Energy Technologies Division , Lawrence Berkeley National Laboratory , 2 Department of Electrical Engineering , University of California at B.* (2003)

[191] C. Blum and A. Roli. *Metaheuristics in combinatorial optimization: Overview and Conceptual Comparison.* (2001)

[192] T. Wortmann *et al. Advantages of surrogate models for architectural design optimization.* (2015)

[193] D. Rutten. *Navigating Multi-Dimensional Landscapes in Foggy Weather as an Analogy for Generic Problem Solving.* (2014)

[194] D. Rutten. *Galapagos: On the Logic and Limitations of Generic Solvers.* (2013)

[195] K. O. Jones. *Comparison of Genetic Algorithm and Particle Swarm Optimisation.* (2005)

to make successive generations [193]. All three are naturally inspired with SA mirroring cooling in a metal, PSO a flock of birds and EAs the process of natural selection. All three approaches are implementable within the parametric design tool Grasshopper which has been used to instantiate the design methodology. SA and EAs are contained within the Galapagos solver [194] and PSO within Silvereye [196]. Each search strategy requires a number of values to be set. These are defined as:

- **PSO:** Number of iterations 60, Max. velocity 0.2, swarm size 20.
- **EA:** Max stagnant 50, Population 50, Initial boost 2x, Maintain 5%, inbreeding 75%, iteration limit 60.
- **SA:** Temperature 100%, Cooling 0.95x, Drift Rate 25%, iteration limit 60.

The values listed above correspond to the default settings within the solvers, initial conditions were also set to their respective defaults.

7.3.1 Results

Ten simulations were run for each solver. The means and standard deviations for the best solution generated in each optimisation run for each parameter and search strategy are shown in Table 7.2. The complete genomes are shown in Figure 7.4 and the variation in outcomes observed in these are discussed in the following section.

Table 7.2 *Outputs of means and Standard Deviations (SDs) from optimisation runs*

	SA		EA		PSO	
Parameter	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Perimeters	4.60	2.76	4.60	1.78	4.20	0.79
Top/Bottom Layers	1.20	0.63	1.00	0.00	1.70	1.34
Layer Height (mm)	0.10	0.06	0.07	0.05	0.08	0.07
Infill (%)	0.30	0.00	0.30	0.00	0.30	0.00
Height (mm)	14.75	7.07	15.97	2.39	17.07	1.37
Width (mm)	15.40	13.32	5.87	1.37	5.00	0.00
Fitness	7.41	2.89	9.56	0.94	10.08	0.35
Material at cross section (mm^2)	63.93	28.78	42.23	4.73	39.71	1.44
Load (N)	400.82	0.66	401.31	1.41	400.88	0.65

[196] J. Cichocka *et al. SILVEREYE– the implementation of Particle Swarm Optimization algorithm in a design optimization tool.* (2017)

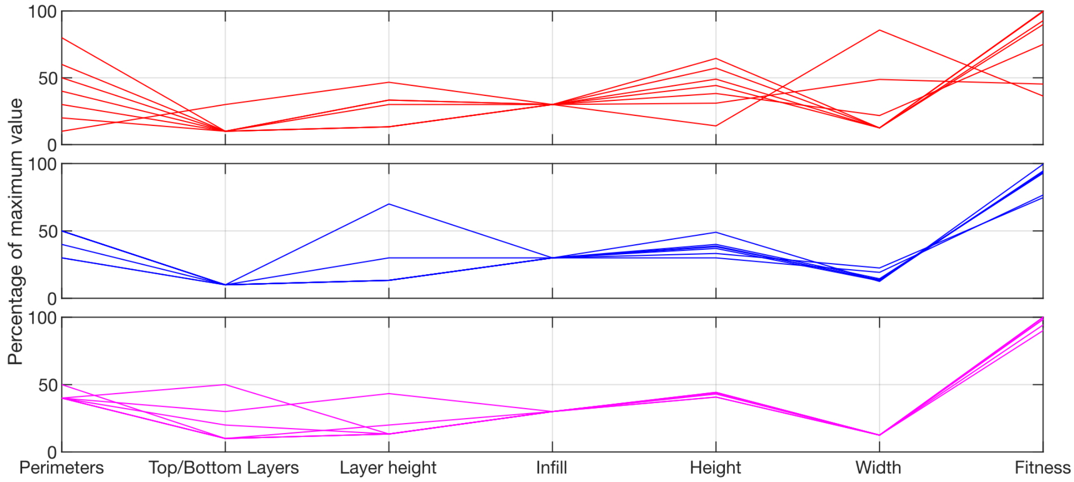


Figure 7.4 *Comparison of search strategies. Top to bottom graphs correspond to Simulated Annealing, Evolutionary Algorithm and Particle Swarm Optimisation respectively. Variables are normalised and expressed as a percentage of their maximum allowable values.*

7.3.2 Discussion

From the results in Table 7.2, it can be seen that PSO consistently generated the best solutions with an average fitness of 10.08 compared to the EA and SA which had values of 9.56 and 7.41 respectively. PSO also had lower variation in outcome with SD of 0.35 compared to 0.94 and 3.89 for EA and SA. PSO also generates solutions that are notably more consistent. This is demonstrated in Figure 4 which shows a much smaller genome variation than in both SA and EA. These results are consistent with those in literature that have found the Silvereye PSO solver to outperform Galapagos' EA and SA solvers with respect to speed and quality of solution [196]. Whilst some parameters converged, others permitted a range of results yielding high fitness values. All solvers minimised infill to the lowest allowable level without compromising print quality, which is to be as expected in bending as the infill provides a lower UTS than the outer shell and will thus contribute less to the second moment of area.

In order to assess the generalisability of these findings, it is important to note that there are no silver bullets with metaheuristics. The no free lunch theorems of optimisation state that no universally better algorithms exist, just some that are better suited for certain problems than others [197]. Whilst PSO has proven best for the instantiation presented, to confirm its superiority for the application of auto-generating manufacturing and geometric parameters for FDM it is nec-

[196] J. Cichocka *et al. SILVEREYE– the implementation of Particle Swarm Optimization algorithm in a design optimization tool.* (2017)
[197] D. H. H. Wolpert and W. G. G. Macready. *No Free Lunch Theorems for Optimization.* (1997)

essary to carry out further testing with different design tasks. In the context of this thesis, this will require the confirmation that PSO is effective in a broader application of the design methodology.

7.4 Conclusion

This chapter has verified the suitability of the tools used in implementing the methodology that can enable the democratisation of design. These are the Rhino CAD package and in-particular its Grasshopper add-on which permits the generation of both parametric structural and functional models which underpin the functionality of the methodology presented in this thesis.

The use of these tools was illustrated through the application of the methodology to the Universal Hook Generator which permitted the assessment and selection of an appropriate metaheuristic algorithm for exploring the solution space and generating solutions. Particle Swarm Optimisation was found to generate the best and most consistent solutions of the metaheuristics trialled.

Whilst providing a useful platform for testing assessing meta-heuristics and the suitability of the tools selected to implement the methodology, a number of further steps need to be undertaken to fully implement the methodology. These steps include incorporating variability into the model to allow the determination of confidence levels of part performance. Build time also needs to be factored into the model as a faster build time might be an attractive trade-off with material usage.

The next chapter will detail the creation of a comprehensive FDM capability profile to be incorporated into the methodology.

Chapter 8

FDM Capability Profiling

Chapter 5 identified the process parameters that impact the mechanical properties of parts (the scope of a capability profile (CP)). Chapter 6 demonstrated the manner in which this CP is integrated within the wider democratising design methodology (the functionality of CP).

This chapter provides a functioning capability profile that meets the requirements of the democratising design methodology. It allows the methodology to be fully implemented and validated in the remainder of the thesis. To achieve the this, the data structure and population of a capability model for FDM is presented. The capability model is populated via experimental testing and is subsequently validated. It contains the following:

- A testing framework and set of methods that permit the generation of a capability profile for FDM.
- A data structure, including how the process information is organised and where it is called up and used in the generative design process.
- A set of experimental test results that underpin the capability model.
- A neural network based generation of a capability model.

8.1 Background

This section gives a short overview of capability profiles demonstrating how they have been incorporated within a Computer Aided process (CAx) for traditional subtractive manufacturing processes. This is contrasted with the manner in which a CP for FDM is incorporated within the democratising design methodology presented in this thesis.

8.1.1 Existing capability models

A capability profile is a time-sensitive image of a manufacturing resource, representing the capabilities that a specific machine tool will be able to provide at a specific time on a specific product [198]. The practice relates the effect that machining parameters have on part properties by accounting for changes to the manufacturing resource over time. When this is coupled with information about the stock material and a part's geometry the characteristics of a workpiece can be described. This can take place at four levels ranging from geometry of the element to the chemical integration at the atomic scale [199]:

- Macro (accuracy in shape and dimension)

[198] S. T. Newman and A. Nassehi. *Machine tool capability profile for intelligent process planning.* (2009)
[199] F. Klocke *et al. Capability Profile of Hard Cutting and Grinding Processes.* (2005)

- Micro (surface topography)
- Meso (material structure and properties)
- Nano (tribo-chemical reaction layers)

Capability profiles can be incorporated in a number of ways within existing CAx chains to support the manufacturing process. The most common CAx chain used in manufacturing today involves the generation of a part in Computer Aided Design (CAD) software. This is then transferred to a Computer Aided Process Planning (CAPP) or Computer Aided Manufacturing (CAM) system where process information is added to the geometry. This information typically includes tool definitions, feeds, speeds and machining strategies. A post-processor is used to move the information from a product space in CAM to the machine space of the CNC [200]. Within this process, CPs are typically used in process planning which consists of the consolidation of activities that seek to define the steps required to alter the shape of raw stock material into the desired product [201]. The use of CPs allows the selection of appropriate manufacturing resources for a given part.

Figure 8.1 shows the process planning process incorporating manufacturing capability profiles. The manufacturing production resource is profiled by combining sensed data from the resource itself, nominal resource information and production policies. These allow tool wear to be measured and compared against an allowable threshold that would yield the manufacture of an acceptable part.

For traditional subtractive methods the development of a number of capability profiles can be found in literature including a capability profile for hard cutting and grinding [199] and a review of machining parameters in the turning process that impactfinished part properties [202]. Additionally, the integrated use of manufacturing resource profiles is proposed in CAPP in order to optimise the generation of process plans [198]. CPs have also been used to provide a tool health data model [203].

8.1.2 A Capability Profile for FDM

When designing for FDM, the manufacturing parameters not only influence the manner in which the physical product is to be made, but also greatly impact the mechanical properties of the deposited material itself and hence the behaviour of

[200] S. T. Newman and A Nassehi. *Universal Manufacturing Platform for CNC Machining.* (2007)
[201] H. A. ElMaraghy. *Evolution and Future Perspectives of CAPP.* (1993)
[202] G. Bartarya and S. K. Choudhury. *State of the art in hard turning.* (2012)
[203] P. Vichare *et al. Machine tool capability profiles for representing machine tool health.* (2015)

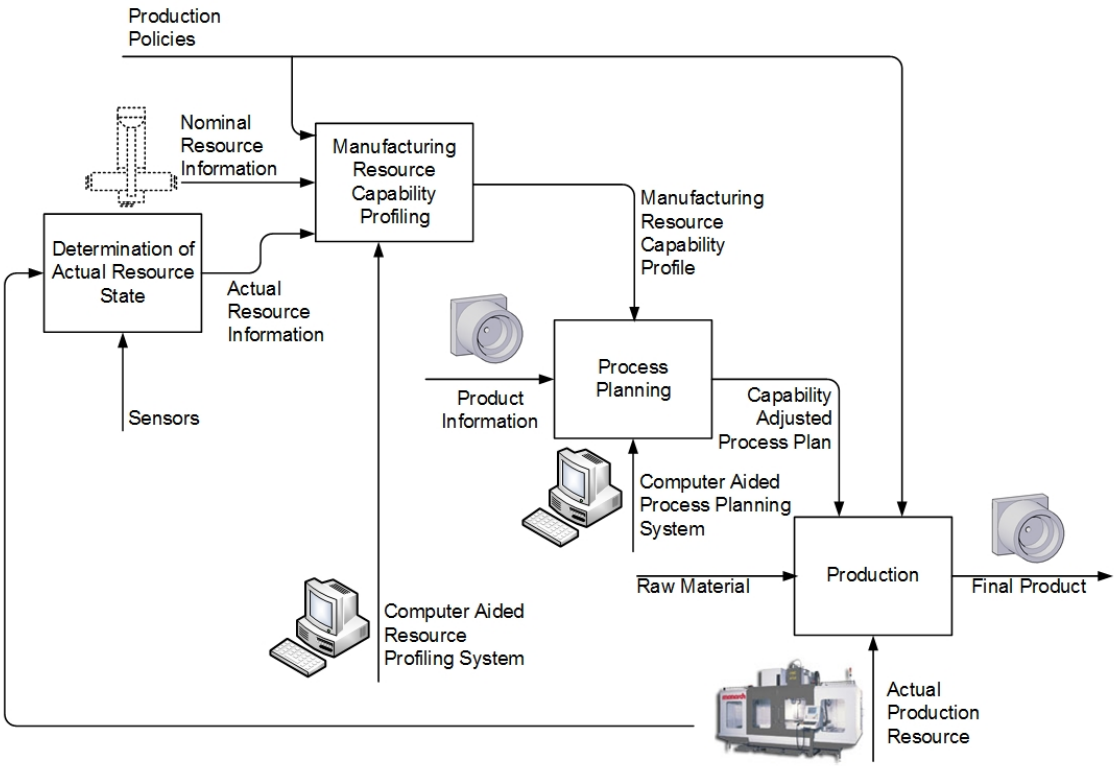


Figure 8.1 *IDEF0 diagram showing incorporation of capability profile in traditional manufacturing process. From [198] reproduced with permission*

the part. A CP for FDM must therefore also consider the design process, as well as the CAPP or CAM stages. To achieve this, it must be included earlier in the design and manufacturing process than with traditional CPs. This is shown in Figure 8.3 where an IDEF-0 representation presents how a capability profile for FDM would be derived and incorporated within a generative design process that concomitantly determines both manufacturing and structural parameters that permit a part to meet its functional requirements.

The process planning for subtractive processes (Figure 8.1) uses the manufacturing resource capability as a control for the process planning stage to transform product information (eg a static CAD model) into a capability adjusted process plan. In the proposed process for FDM (Figure 8.3) however, it uses it as a control to generate structural and manufacturing parameters based upon the object requirements. As such, manufacturing capability is incorporated in the design of the product.

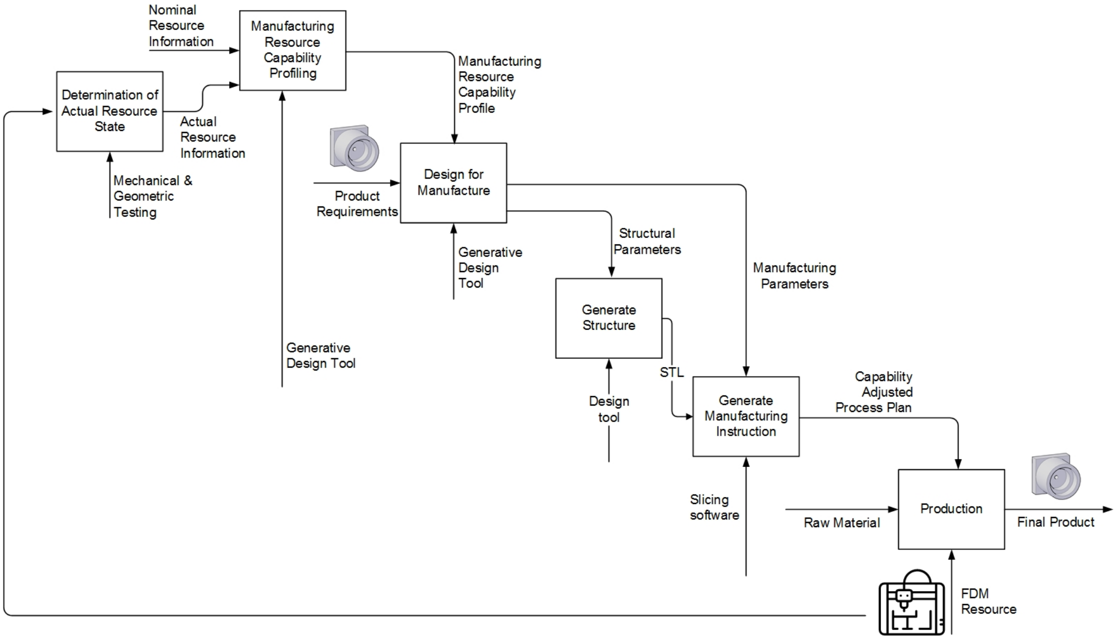


Figure 8.2 *IDEF0 diagram showing general incorporation of capability profile in design and manufacture process for FDM*

8.2 Design Parameters for FDM

A CP for FDM provides the presented design methodology with a foundation upon which design decisions can be made. Within this it is necessary to include the parameters which have the most significant impact on the properties of finished parts. Chapter 5 characterised the FDM manufacturing process and demonstrated the general impact directives of manufacturing parameters on the behaviour of finished parts. These provide a basis to screen parameters and draw those together that can be observed to significantly alter a part's mechanical properties. These are summarised in Table 8.1. These parameters can subsequently be divided into three groups according to the nature of the impact they have on the manufactured part:

- Group 1 consists of those that directly affect a part's mechanical behaviour by altering the material properties (such as UTS or Young's Modulus).
- Group 2 parameters affect the post-slice geometry and thus alter the shape properties of parts.
- Group 3 includes those parameters that affect both of the above (layer height for example alters the UTS but also influences the way geometry is sliced).

Figure 8.3 shows an IDEF0 diagram of how the defined groups of manufacturing parameters are used to elicit a part's mechanical behaviour. Specific material properties are calculated by adjusting a normative set of properties with the effects caused by manufacturing parameter groups 1 & 3 and are defined for both infill and solid shells. Part geometry is sliced incorporating manufacturing parameter groups 2 & 3. The sliced geometry provides area moments and quantities of material for both infill and solid shells. When combined with the specific material properties these enable the prediction of a part's mechanical behaviour.

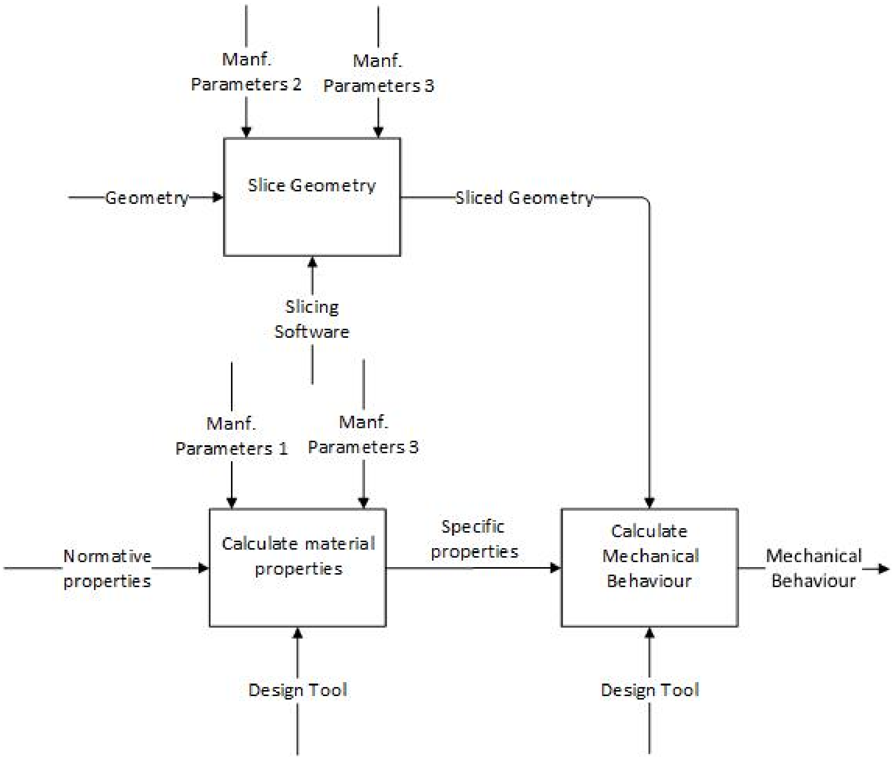


Figure 8.3 *IDEF0 diagram demonstrating how manufacturing parameters are incorporated and used in the capability profile*

Table 8.1 *Parameters required to define the FDM search space*

Parameter	Impacts material property?	Impacts sliced geometry?	Parameter Group
Extrusion Temperature	Yes – affects quality of raster adhesion [162]	-	1
Material Type	Yes – distinct properties for different materials [167]	-	1
Variability	Yes – distribution distinct for printers and materials	-	1
Raster Angle	Yes – greater strength when raster is in direction of applied load [161]	-	1
Infill pattern	Yes – gives varied properties in different directions [162]	-	1
Raster Width	-	Yes - impacts solid shells as these must be in increments of raster width [161]	2
Infill Percentage	-	Yes – affects amount and distribution of material [162]	2
Top/Bottom Layers	-	Yes – affects amount and distribution of material	2
Solid Shells	-	Yes – affects amount and distribution of material	2
Layer height	Yes - Increase in layer height increases strength [162]	Yes - Vertical dimensions are discretised in increments of layer height	3
Build Orientation	Yes - properties vary in different orientations [162]	Yes - Directional discretisation varies depending on build direction	3

8.3 Population of a capability profile

In order to generate a usable capability profile, it is necessary to undertake testing on a single printer [168]. To define the parameters that will be included within aCP, a number of parameters can be dis-regarded from those defined in Table 8.1 for the next phase of testing. These along with their relevant reasoning are listed below:

- **Infill pattern** - There are a large number of infill types and to adhere as closely as possible the specimen sizes dictated by the ASTM standards, it isn't possible to generate specimens that have full infill patterns. The effect provided by the infill pattern, therefore, cannot be determined.
- **Extrusion Temperature** - whilst this is shown to have a significant effect, a parabolic relationship is shown with an optimum strength occurring at a material specific temperature [162]. This is a value that can therefore be prescribed by the material manufacturer and doesn't require experimental determination at this stage.
- **Raster Angle** - this is typically determined by the slicing software and is often a property of the infill pattern. As such, it is not a variable that can be readily controlled by the user.
- **Raster Width** - This is defined by the printer's nozzle width and is therefore unlikely to be changed.
- **Material type** - Different materials will have different properties and as such distinct data sets within a capability profile. The scope of testing to be carried out here is to determine a single data set for one material. Further work would see this expanded with further materials considered.
- **Variability** - this has already been determined in the previous chapter where the FDM manufacturing process was characterised. It will be incorporated in the full implementation of the methodology.

[168] P Hemalatha *et al. Additive manufacturing: opportunities and constraints A summary of a roundtable forum held on 23 May 2013 hosted by the Royal Academy of Engineering Additive.* (2013)

[162] A. Alafaghani *et al. Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach.* (2017)

The parameters to be tested in order to generate an FDM capability profile are as follows:

- **Layer height**
- **Build orientation**
- **Infill percentage**
- **Top / Bottom layers**
- **Solid Shells**

These are selected as they are shown to significantly impact the mechanical behaviour of a part, the characteristics of the print and are also commonly selected by the user. The effect that these have will be determined through experimental testing as detailed in the following sections.

8.4 Experimental method

Design of experiements (DOE) is the technique of defining and investigating all possible conditions in an experiment involving multiple factors [204]. The first and most exhaustive method of doing this is via use of a full factorial approach. This involves the testing of all combinations of parameters. For example, 5 parameters at 3 levels with 6 repeats each would require $6 * 3^5$ (1458) tests. If runs are expensive and time is short, this could understandably be considered quite impractical.

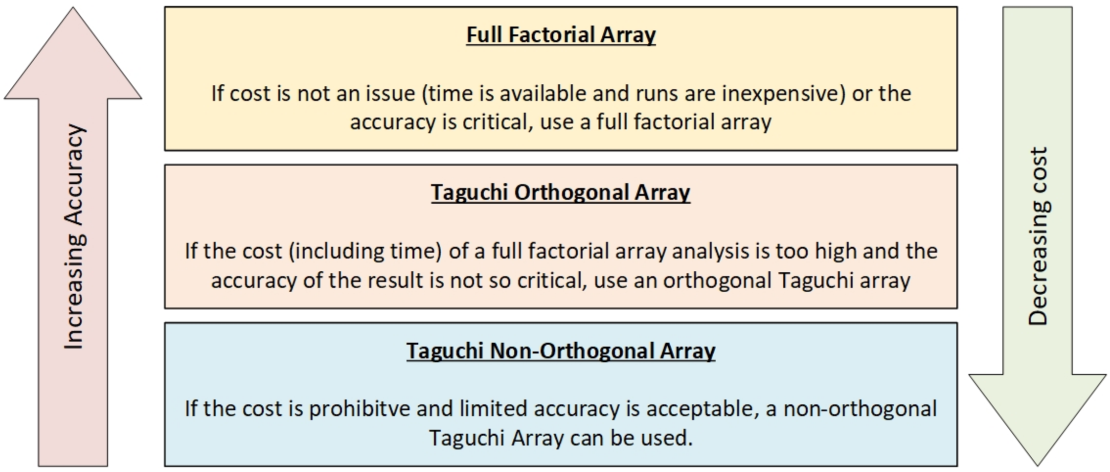


Figure 8.4 *Pros and cons of different experimental approaches. Adapted from [205]*

An alternative is to use a fractional or partial factorial approach. Where a carefully selected subset of experimental runs are undertaken. Whilst this greatly

[204] R. Ranjit. *A PRIMER ON THE TAGUCHI METHOD.* (2010)

reduces the time taken to undertake the experimental testing, rigorous mathematical treatment is required in the design of the study and of the produced results and the same experiment can be undertaken a number of different ways, making replicability difficult [204].

Another alternative to this is the Taguchi method - an innovative method proposed by Dr. Genichi Taguchi that simplifies and standardises fractional factorial design. It can be considered a type of partial factorial approach but involving the use of pre-set orthogonal arrays to define the experiments that need to be undertaken. Because these are pre-set, the experimental set-ups are repeatable. The application of a Taguchi orthogonal array considering 5 parameters at 3 levels necessitates 18 experimental tests times 6 repeats, yielding a total of 108 tests.

Figure 8.4 demonstrates the trade-off between the use of full factorial experimental design and both orthogonal and non-orthogonal Taguchi arrays. Because of these benefits, the use of a Taguchi orthogonal array is selected in order to define the experimental tests that needed to be undertaken in the generation of an FDM capability profile.

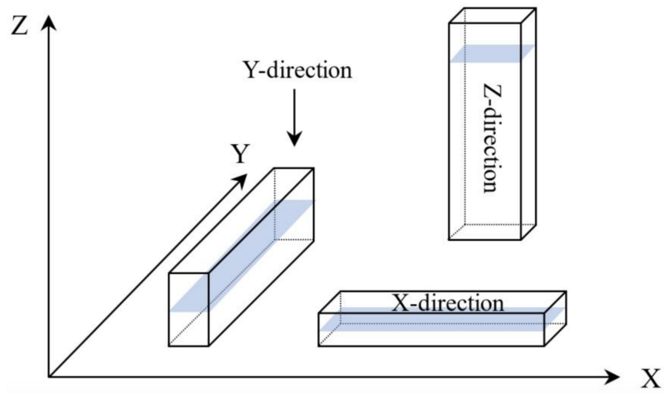


Figure 8.5 *Three principle FDM build orientations considered in capability profiling. From [206] licensed under creative commons*

8.4.1 Parameters and levels

The parameters previously defined for capability profiling need to be tested at three levels each. This is to allow for the possibility that a variable's effect is non-linear [204]. The selected parameters exhibit a number of interdependencies. For example, layer height must be a factor of all increments of top/bottom layer thickness. These various constraints framed the values selected. The justification for the levels chosen for each of these tests are as follows:

- **Layer height:** Needs to be a factor of top/bottom layers and also permit a realistic range of printable layer heights. In Cura slicing software [207], 0.1mm is considered 'fine' and 0.3mm is the maximum permissible value without the generation warning.
- **Build Orientation:** the three principle build orientations were considered (X, Y & Z). These are shown in Figure 8.5
- **Infill Percentage:** infill percentages below 20% can often yield unsuccessful prints so this was used as a minimum. 100% is a natural maximum for infill percentage.
- **Top/Bottom Layers:** These were defined according to the design of the test specimen. Double this value could not exceed specimen thickness, it also needs to be an increment of all values of layer height.
- **Solid Shells:** These needed to be a multiple of nozzle width (0.4mm). Additionally, double this value could not exceed specimen width.

Based upon these requirements, the levels of the independent variables could be defined. These are shown in Table 8.2.

Table 8.2 *Parameters and levels*

Parameter	Level 1	Level 2	Level 3
Layer height (mm)	0.1	0.2	0.3
Build Orientation	X	Y	Z
Infill Percentage (%)	20%	60%	100%
Top / Bottom Layers (mm)	0.6	1.2	1.8
Solid Shells (mm)	0.4	1.2	2

A corresponding Taguchi orthogonal array of 5 variables at 3 levels is used to define the experimental runs that need to be undertaken [205]. This is shown in Table 8.3.

[204] R. Ranjit. *A PRIMER ON THE TAGUCHI METHOD.* (2010)
[207] Ultimaker. *Cura.* 2019
[205] M. J. Cimbala. *Taguchi Orthogonal Arrays.* 2014

Table 8.3 *Orthogonal array with 5 parameters at 3 levels. Levels correspond to those defined in Table 8.2*

	Levels				
Sample	**Layer height**	**Infill percentage**	**Top / Bottom Layers**	**Solid Shells**	**Build orientation**
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	2	1	1	2	2
5	2	2	2	3	3
6	2	3	3	1	1
7	3	1	2	1	3
8	3	2	3	2	1
9	3	3	1	3	2
10	1	1	3	3	2
11	1	2	1	1	3
12	1	3	2	2	1
13	2	1	2	3	1
14	2	2	3	1	2
15	2	3	1	2	3
16	3	1	3	2	3
17	3	2	1	3	1
18	3	3	2	1	2

In addition to the samples designated by the Taguchi array, three additional sets of samples were manufactured and tested. These represented parameter sets not considered in the array and would be used to validate a generated capability profile once it was generated. These additional parameter sets are shown in Table 8.4

There a number of methods to calculate necessary sample size. The National Institute of Science and Technology [208] prescribes the use of Equation (8.1) to calculate the necessary sample size.

$$N = (z_{1-\alpha/2} + z_{1-\beta})^2 \left(\frac{\sigma}{\delta}\right)^2 \tag{8.1}$$

where N is the required sample size, σ the standard deviation , $z_{1-\alpha/2}$ t& $z_{1-\beta}$ are values from a normal distribution according the required likelihoods of a

[208] National Institute of Science and Technology. *Engineering Statistics Handbook*. (2013)

false positive (α) or false negative (β) and type of test, δ is the expected observed change between samples.

The observed difference from the testing carried out in the Characterisation of the FDM Manufacturing Process Chapter found a difference of approximately 10 MPa between samples printed with infills of 20 and 100 percent. A smaller value of 4 MPa is used as the increments for the orthogonal array are smaller than those in these initial experiemnts. The standard deviations of these experiments were found to be approximately 2.3 MPa. A two-sided test with α error 5% yields $z_{1-\alpha/2}$ a value of 1.96. $z_{1-\beta}$ with a power (likelihood of false negative) of 80% yields a value of 0.8416. The required sample size is subsequently calculated to be 5.19 which is congruent with the ASTM designated sample sizes of five for tensile tests [169].

Samples will therefore be manufactured and tested in batches of six to allow for a single sample to be disregarded in the case of manufacturing defects or testing errors.

Table 8.4 *Validation samples. Parameter levels correspond to those defined in Table 8.2*

Sample	**Layer height**	**Infill percentage**	**Top / Bottom Layers**	**Solid Shells**	**Build orientation**
21	2	2	2	2	2
22	1	1	2	3	1
23	3	3	2	1	3

8.4.2 Tensile test method

The experimental test set-up consisted of a tensile test machine, video gauge and test lamp for illuminating the test specimen. These are all shown in Figure 8.6

The tensile tests were carried out on a 25kN Instron 8872 test machine. Testing was carried out across multiple days over the course of approximately a week. Depending on the test days, the machines were fitted with either 5kN or 10kN load cells. All tests were carried out with break loads within the recommended ranges for the load cells. Specimens were extended at a rate of 1 mm/min until failure. Instron's Wave Matrix software was used to execute the testing and export values of applied load.

Extension was measured using an iMetrum video gauge and software. This was

[169] ASTM International. *Standard test method for tensile properties of plastics.* (2003)

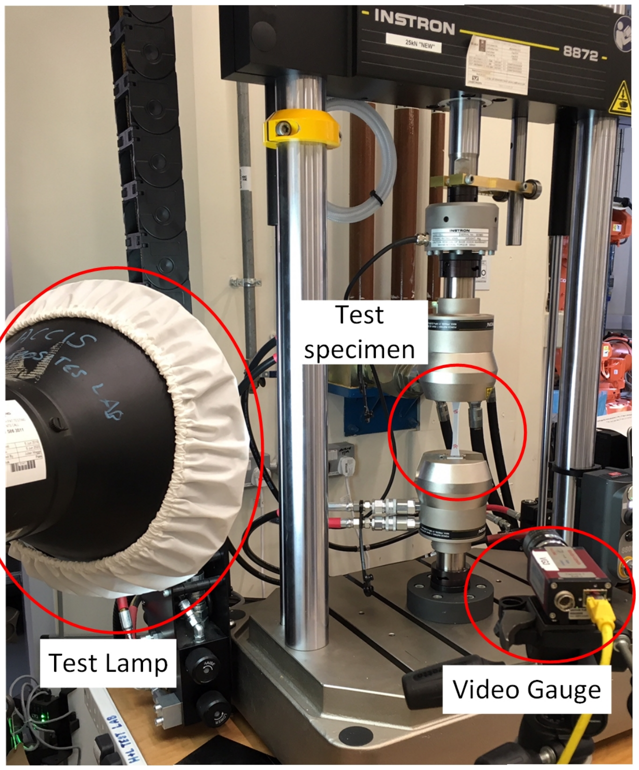
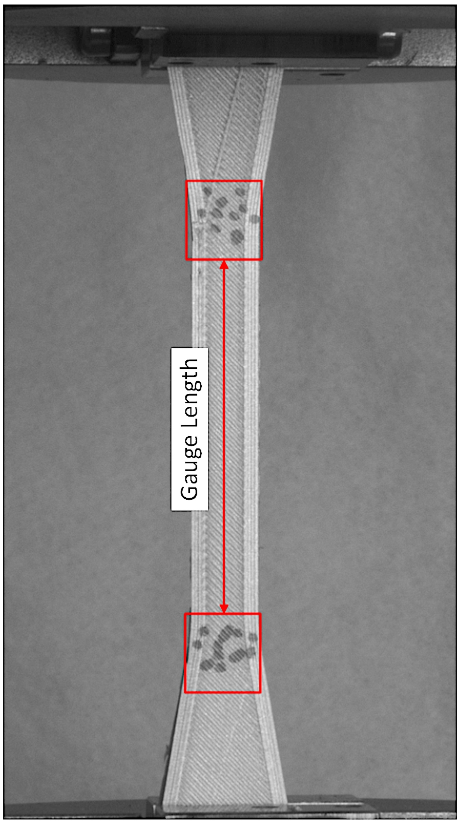


Figure 8.6 *Experimental set-up*

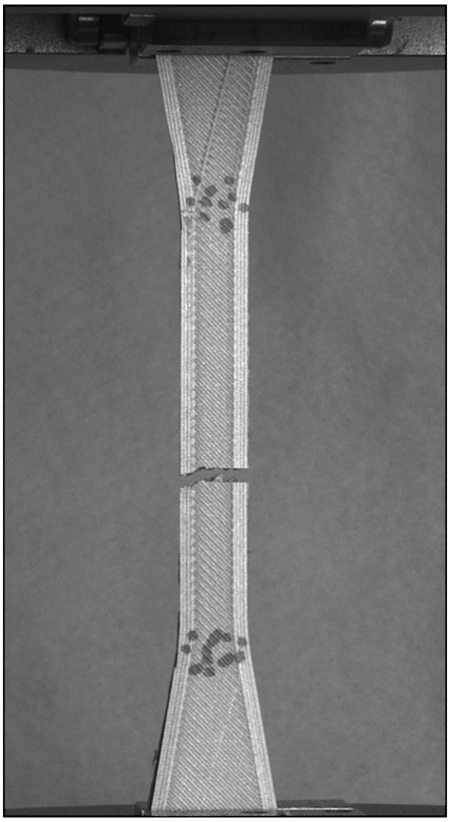
used to track the distance between a set of points at either end of the reduced section of the test specimen. The tracking points are shown in Figure 8.7a for a specimen mid-test. The iMetrum software receives the load output from the Instron machine in real time, and combines them with measured extension to provide load, extension values from the tests. These values were output in .CSV format for analysis in Excel and Matlab. Test videos were also exported. Two stills from these are shown in Figure 8.7a and Figure 8.7b showing a test specimen pre and post-test respectively.

8.4.2.1 Test specimen

The test specimen used for the experimental tests is adapted from the ASTM standard specimen in order to accommodate for the defined values of the independent variables. Its major dimensions are shown in Figure 8.8.



(a) *Labelled specimen demonstrating points used for extension tracking*



(b) *Specimen post-test demonstrating failure in reduced section.*

Figure 8.7 *Stills from video gauge footage*

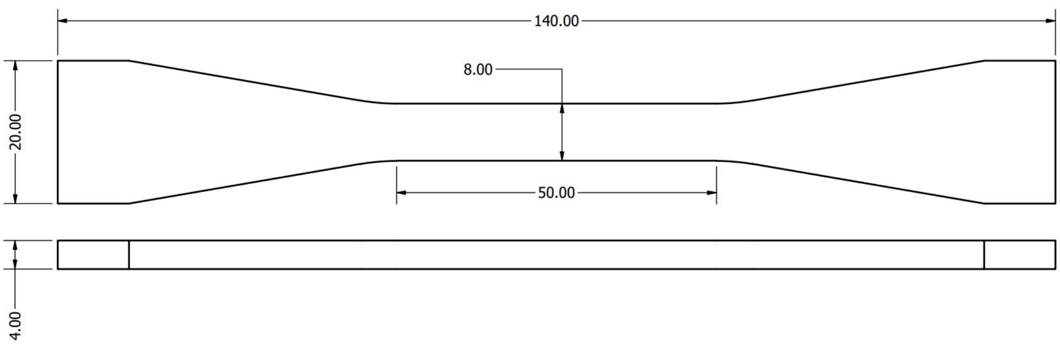


Figure 8.8 *Major dimensions of test specimens used for capability profiling*

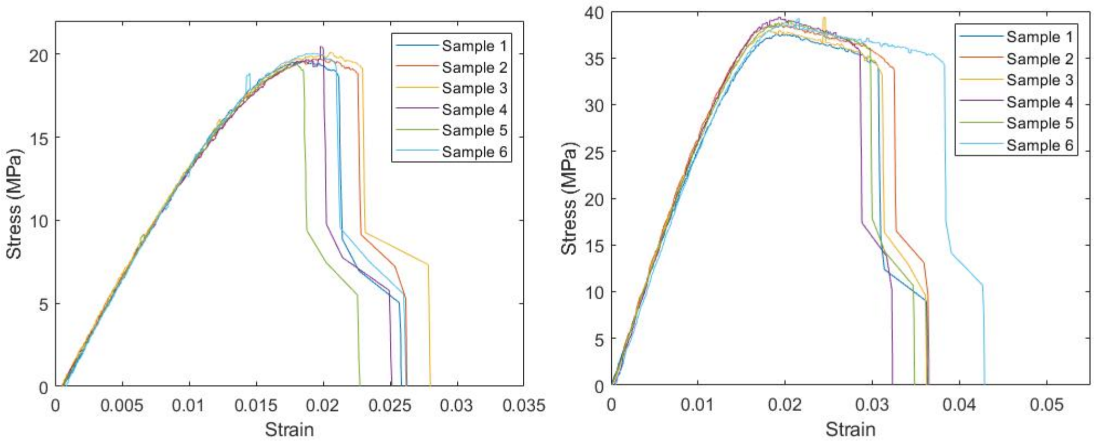
8.5 Results

The results of the tensile tests carried out are shown in Table 8.5. These show the measured parameters of cross sectional area, break load and extension in mm. Three calculated parameters are also shown. UTS is calculated as the max load divided by the cross sectional area. Strain at UTS is calculated as extension divided by gauge length expressed as a percentage.

Elastic Modulus (E) was calculated by using Matlab's polyfit function to fit a straight line on points between 10% and 60% of the maximum load for each individual specimen.

Samples 1-18 correspond to the Taguchi orthogonal array demonstrated in Table 8.3. Samples 21, 22, & 23 are parameter combinations from outside of this array which were manufactured and tested to validate the capability profile generated.

Stress-strain graphs for all samples are included in Appendix A. All tests followed the expected curve for failure of plastics. Figure 12.1 shows the stress-strain graphs for two test samples to demonstrate the typical curves obtained and the consistency of results.



(a) *Parameter set 1* (b) *Parameter set 2*

Figure 8.9 *Stress Strain Graphs for tensile tests 1 & 2*

Table 8.5 *Results from tensile testing. Standard Deviation is abbreviated to SD. Number of samples are represented by n.*

Sample		Measured Paramters						Calculated Parameters					
		Cross sectional Area (mm^2)		Max Load (kN)		Extension (mm)		UTS (MPa)		% Strain @ UTS		E (Gpa)	
	n	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	6	32.09	0.097	0.64	0.012	1.16	0.166	19.83	0.44	1.75	0.27	1.345	0.05
2	6	33.23	0.099	1.24	0.022	1.56	0.230	37.39	0.67	2.23	0.29	2.54	0.09
3	6	32.71	0.256	1.35	0.021	1.33	0.232	41.31	0.53	2.04	0.30	3.28	0.14
4	6	33.48	0.281	0.89	0.041	1.18	0.133	26.74	1.35	1.90	0.25	1.951	0.06
5	6	33.42	0.441	1.11	0.051	1.05	0.114	33.30	1.26	1.70	0.13	2.654	0.25
6	6	32.04	0.420	1.55	0.093	1.01	0.048	48.39	3.11	1.67	0.08	3.201	0.03
7	4	32.14	0.151	0.25	0.006	0.61	0.020	7.88	0.22	1.00	0.03	0.906	0.01
8	6	30.80	0.387	1.22	0.068	0.89	0.065	39.72	2.31	1.48	0.09	3.05	0.09
9	6	33.37	0.086	1.39	0.037	1.03	0.049	41.55	1.14	1.82	0.09	2.952	0.16
10	4	32.17	0.178	1.66	0.031	1.36	0.659	51.54	1.07	2.37	1.17	3.464	0.20
11	5	31.79	0.347	0.63	0.307	0.66	0.323	23.53	0.26	1.34	0.06	2.33	0.03
12	5	30.38	0.929	1.32	0.062	0.86	0.425	43.49	0.83	1.93	0.13	3.019	0.09
13	6	31.30	0.228	1.12	0.090	0.97	0.160	35.86	2.88	1.73	0.26	2.543	0.08
14	6	33.88	0.093	0.92	0.021	1.14	0.064	27.22	0.68	1.97	0.11	2.083	0.06
15	6	33.52	0.150	1.00	0.014	0.93	0.106	29.83	0.47	1.71	0.15	2.458	0.09
16	5	33.43	0.147	0.51	0.061	0.69	0.128	15.26	1.85	1.28	0.26	1.77	0.06
17	6	30.13	0.233	0.69	0.122	0.63	0.142	22.78	3.90	1.17	0.26	2.302	0.03
18	6	33.25	0.252	1.43	0.026	1.13	0.043	43.06	0.72	1.99	0.08	3.078	0.06
21	5	32.93	0.221	2.03	0.058	1.06	0.099	61.61	2.15	1.91	0.18	4.12	0.28
22	6	29.62	0.364	2.97	0.043	1.28	0.094	100.24	1.05	2.28	0.19	6.4	0.21
23	6	33.13	0.144	1.49	0.048	0.62	0.043	44.89	1.39	1.11	0.09	4.253	0.37

8.6 Identification of general trends

The Taguchi method permits the elucidation of the impact a parameter has on the output of a process. The normalised effect of a variable can be calculated by using Equation (8.2).

$$\bar{A}_1 = 1/n \sum_{i=1}^{n} Y\{A_1\} \tag{8.2}$$

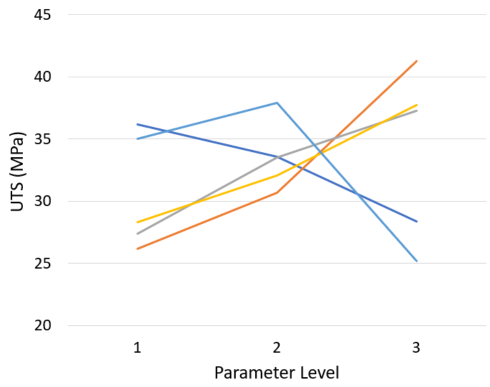
where Y_i is an output (for example UTS) based upon the set of inputs $\{A, B, C, D, E\}$. A, B, C, D and E correspond the manufacturing parameters considered in the capability profile formation. $\bar{A}_1$ represents the normalised effect of all values featuring parameter A at level 1. Normalised values can be calculated in order to determine the effect that each manufacturing parameter has on the dependent variables. Values were calculated for all parameters at all three levels.

Figure 8.10a shows the effect that the manufacturing parameters have on UTS. *Infill percentage*, *top/bottom layers* & *solid shells* are all shown to increase UTS. Of these, the effect of *infill percentage* is highest with a 15 MPa difference between levels 1 & 3. Increasing *layer height* can be seen to have a negative effect on UTS. *Build orientation* (a categoric variable) is shown to impact UTS with specimens printed in the Y direction (3 MPa) stronger than those in the X direction and significantly stronger than those in the Z direction (10 MPa).

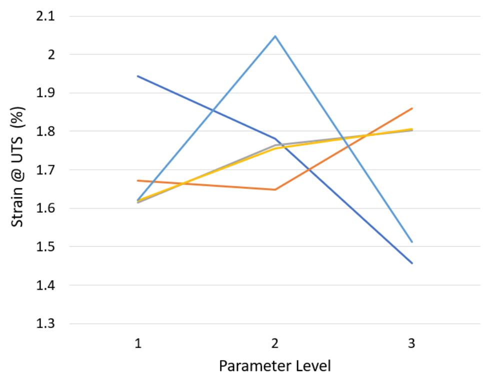
Figure 8.10b shows the effect that manufacturing parameters have on strain at UTS. Slight positive relationships can be observed between *infill percentage, top/bottom layers* and *solid shells*. A strong negative relationship exists between *layer height* and strain at UTS. *Build orientation* also has a large impact, with extension much larger in the Y direction (2%) compared to the X (1.6%) and Z (1.5%) directions.

Figure 8.10c demonstrates the effect that manufacturing parameters have on Elastic Modulus. The relationships are similar to those for UTS, with infill percentage, Top/Bottom layers and solid shells all exhibiting positive relationships with Elastic Modulus and layer height a negative one. Elastic Modulus is shown to be highest for specimens printed in the Y direction, and lowest in the Z direction.

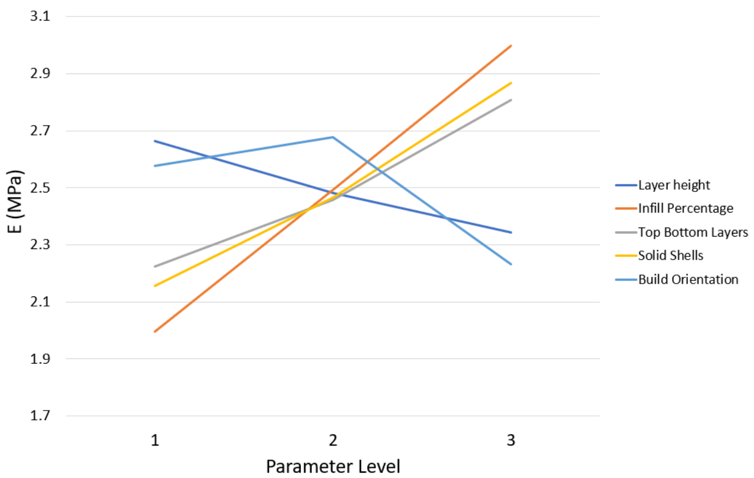
Consolidation of the findings from Figure 8.10 permits the conclusion that the parameters all have significant effects on the maximum load a part will be able to withstand. In addition to this, although to a lesser degree, the manner in which a part fails depends on the manufacturing parameters as extension at



(a) *Effect of parameters on samples' UTS*



(b) *Effect of parameters on samples' Strain @ Break*



(c) *Effect of parameters on samples' Elastic Modulus*

Figure 8.10 *Graphs demonstrating normalised effect of variables*

maximum load as well as Elastic Modulus vary greatly.

This analysis has allowed the qualitative evaluation of the effect of parameters, but does not permit the prediction of a part's mechanical properties given a set of input values.

8.7 Development of capability profile

The purpose of the experimental tests undertaken was to permit the generation of a CP for FDM that would permit the prediction of mechanical properties based upon an input set of manufacturing parameters. This section details the approaches used to generate this CP.

8.8 Multiple Linear Regression

A multiple regression is an extension of simple linear regression and is used to predict a continuous dependent variable based on multiple independent variables. It also permits the determination of overall fit of the model, and the relative change in the dependent variable caused by each independent variable [209].

It was deemed an appropriate means of generating an FDM capability profile because the dependent variable is continuous, there are two or more independent variables and the necessary output is a predictive model.

To undertake a multiple linear regression a number of assumptions need to be satisfied [210]. These are as follows:

1. The dependent variable is *continuous*.
2. There are *two or more independent variables*.
3. Independence of observation exists requiring a test for *first order auto-correlation*.
4. A *linear relationship* needs to exist between each independent variable and the independent variable.
5. The data shows *homoscedasticity of residuals* with variance along the line of best fit being consistent.
6. The independent variables do not demonstrate high levels of *co-linearity*.
7. There are *no significant outliers, high leverage points or highly influential points*.
8. The residuals are approximately *normally distributed*.

The multiple linear regression and tests to assess whether the above assumptions could be met were carried out using IBM SPSS Statistics.

Build orientation needed to be treated as a dummy variable in order it to be incorporated within the linear regression [211] . This is the process of converting a normative variable with n levels into $n-1$ dummy variables. Build orientation was redefined by two binary variables of X & Y. X direction build corresponds to a value of 1 0, Y to a value of 0 1 and Z to a value of 0 0.

Multiple regression was first carried out on the initial 103 tests from the 18 sample sets included in the Taguchi Orthogonal array. These would be subsequently used to predict the behaviour of the the validation sample sets.

[209] Laerd Statistics. *Multiple regression using SPSS Statistics.* 2015
[210] R. T. S. Laurent and W. D. Berry. *Understanding Regression Assumptions.* (1994)
[211] E. R. Ziegel and M. Hardy. *Regression with Dummy Variables.* (1994)

For regression on the initial 18 sample sets ndependence of residuals was *not* observed, as assessed by a Durbin-Watson statistic of 0.469. Whilst the other conditions for undertaking a multiple linear regression were not violated, as errors have been shown to be correlated, multiple liner regression is not an appropriate analysis technique. The same is found when regression is carried out on all 21 sets of samples.

Accordingly, the models generated were unable to generate accurate predictions of the dependent variable of UTS as demonstrated in Table 8.6, where average predicted error is 36% for the 18 samples and 26% when carried out on all 21.

Regression was also carried out on the average results for each sample sets. Whilst the assumptions for carrying out a multiple linear regression were met, the generated model was unable to predict reliably as shown in Table 8.7. On average its prediction was 36% below a part's actual performance.

In addition to this, the upper and lower bounds for a 95% confidence interval had a large range of up to 60% of the predicted value. The prediction for sample set 23 was for a UTS of 24 MPa with upper and lower bounds of 15 MPa and 33 MPa respectively. Its actual UTS is measured as 44.9 MPa which is much higher than the predicted value and also does not lie within the upper and lower bounds for a 95% confidence interval. As such, it can be concluded that this model and the two others generated via multiple linear regression are not able to adequately predict part performance.

Table 8.6 *Results from multiple linear regression, demonstrating the predictive capabilities of the models generated*

		18 Sets		All data (21 sets)	
Sample Set	**Actual UTS (MPa)**	**Predicted UTS (MPa)**	**% Difference to actual**	**Predicted UTS (MPa)**	**% Difference to actual**
21	61.6	37.9	-38.47	40.8	-33.77
22	100.2	36.106	-63.97	51	-49.10
23	44.9	24.3	-45.88	22	-51.00
10	51.5	44	-14.56	53	2.91
11	23.5	19.3	-17.87	23.63	0.55
		Average	-36.15	**Average**	-26.08

Table 8.7 *Results from multiple linear regression on sample sets' averages*

		18 Sets Averages			
Sample Set	**Actual UTS (MPa)**	**Predicted UTS (MPa)**	**Upper bound (MPa)**	**Lower Bound (MPa)**	**% Difference to actual**
21	61.6	37.9	32	43	-38.47
22	100.2	36	27	45	-64.07
23	44.9	24	15	33	-46.55
10	51.5	43	34	53.08	-16.50
11	23.5	19.54	10.42	28.48	-16.85
				Average	-36.49

8.9 Neural Networks

Due to multiple regression being un-suitable for the dataset, neural networks were used instead in order to generate a model. Neural networks 'consist of many simple, connected processors called neurons, each producing a sequence of real-valued activations. Input neurons get activated through sensors perceiving the environment, other neurons get activated through weighted connections from previously active neurons. Learning or credit assignment is about finding weights that make the neural network exhibit some desired behaviour' [212]. In the generation of a capability profile for FDM this entails the prediction of a part's mechanical properties based upon an input of manufacturing parameters.

The advantages of predictive modelling through the use of neural networks include their ability to detect all possible interactions between independent variables and their implicit ability to detect complex non-linear relationships. This is achieved through a black-box and as such a drawback of this exists in there being limited ability for identification of possible causal relationships [213]. For this reason, multiple-linear regression was attempted prior to the use of neural networks.

In order to use NN a re-arrangement of the input data was necessary. Whereas previously 18 samples were to be used to generate the CP and 3 to validate it, neural networks divide the input data into training and trials. The validation is therefore undertaken iteratively as the model is generated. Because of this, the three additional sample sets were pooled with the initial 18 to increase the

[212] J. Schmidhuber. *Deep Learning in neural networks: An overview.* (2015)
[213] J. V. Tu. *Advantages and disadvantages of using artificial neural networks versus logistic regression for predicting medical outcomes.* (1996)

number of samples used in training the neural network.

8.9.1 Method

IBM SPSS 24 was used to generate a predictive model via use of a multi-layer perceptron neural network. The data was auto-partitioned into training, test and hold-out categories to a ration of 6:2:2. Training data is used to train the neural network, test data to assess the performance of the network and iterate it. Hold-out data is used to validate the final generated model and as such is not involved in the training of the network.

All 21 sets of data were pooled together yielding a total of 120 samples. Stopping criteria for the network was set at 1000 steps passing without improvement in performance with a minimum relative change in training error of 0.0001.

Batch training was used to generate the neural network. This means the synaptic weights are updates only after passing all the training data. This is the generally preferred method of training as it directly minimises total error. It is most suitable for 'smaller' datasets [214].

Neural networks consist of three classes of layers, which are categorised as input, hidden and output [215]. Input and output layers are straightforward to determine as they are singular, and consist of neurons that represent the requisite inputs and outputs. Determining the number of hidden layers and nodes, on the other hand, is considered to be the most challenging aspect of neural network design and there are no proven methods of determining this *a priori* [216].

The number of neurons selected is very important. If too few neurons are used, under-fitting can occur. This means it is not possible to adequately detect the signals in a complicated data set. If too many neurons are used then the neural net has too much information processing capacity, and the limited information in the training set is insufficient to train it. Too many neurons also greatly increase the training time for a network [217].

To generate a neural network for capability profiling, more than zero hidden layers are necessary as the results of multiple linear regression demonstrated that the capability profile could not be represented by linear separable functions or decisions. Neural networks with one hidden layer 'can approximate any function

[214] IBM SPSS. *IBM SPSS Neural Networks 22*
[215] A. Gad. *How Many Hidden Layers/Neurons to Use in Artificial Neural Networks?* 2018
[216] A. J. Thomas *et al. On predicting the optimal number of hidden nodes.* (2016)
[217] J. Heaton. *Artificial Intelligence for Humans, Volume 3: Deep Learning and Neural Networks.* (2015)

that contains a continuous mapping from one finite space to another' [218]. This describes the scenario we are trying model and is therefore deemed a suitable number.

The number of nodes within this neural network will be decided upon automatically by the SPSS software. Automatic architecture selection in SPSS computes the 'best' number of units in the hidden layer. Maximum and minimum values for neurons in the hidden layer were bounded with maximum and minimum values of 50 and 1 respectively.

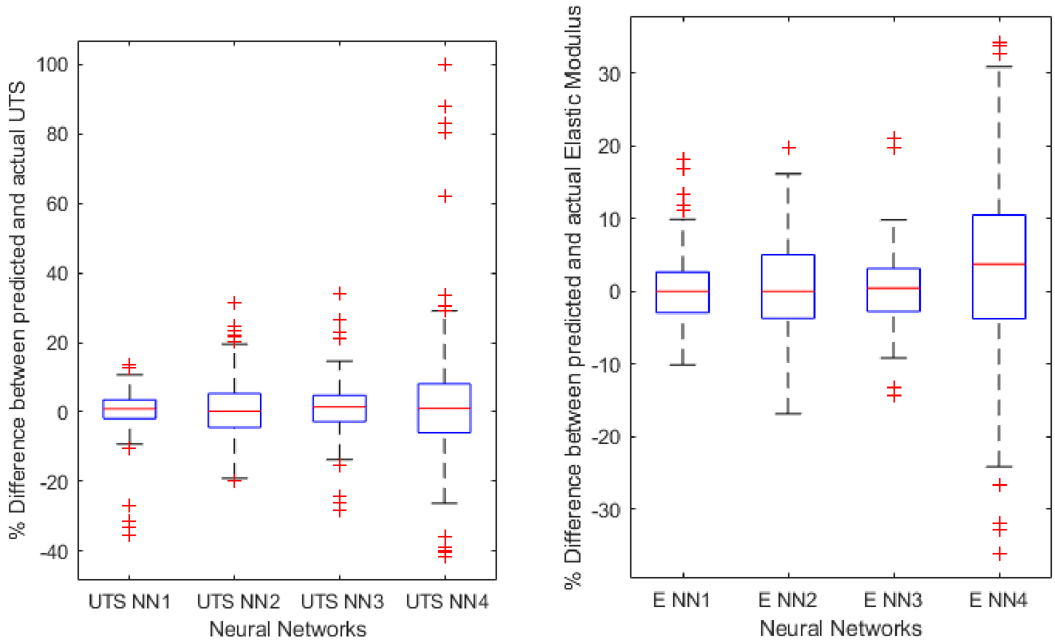
8.9.2 Results

Using the settings outlined in the previous section, four neural networks were generated as potential capability profiles for FDM. Their performance was assessed with respect to their abilities to predict mechanical properties of UTS and Elastic Modulus. Figure 8.11 demonstrates the spread of percentage errors for each neural network when compared to the actual tested values. Table 8.8 shows the average percentage errors with respect to their predictive performance. The difference is in reference to the predicted value when compared to the actual value meaning a negative value corresponds to an under-prediction and a positive value to an over-prediction.

Table 8.8 *Table comparing performance of neural networks generated. Standard Deviation is abbreviated to SD.*

		Absolute				Magnitude			
		Mean	**SD**	**Max.**	**Min.**	**Mean**	**SD**	**Max.**	**Min.**
NN1	**UTS**	-0.4%	8.1%	13.7%	-35%	5.0%	6.4%	35.4%	0.1%
	E	0.4%	5.1%	18.3%	-10%	3.5%	3.5%	18.3%	0.0%
NN2	**UTS**	0.7%	9.7%	31.2%	-20%	7.0%	6.7%	31.2%	0.0%
	E	0.5%	6.1%	19.8%	-17%	4.7%	3.7%	19.8%	0.0%
NN3	**UTS**	0.7%	8.8%	34.2%	-28%	6.0%	6.5%	34.2%	0.0%
	E	0.6%	6.0%	21.2%	-14%	4.1%	4.2%	21.1%	0.0%
NN4	**UTS**	3.7%	22.1%	99.7%	-41%	13.4%	17.9%	99.7%	0.0%
	E	3.2%	14.5%	34.4%	-36%	10.4%	10.0%	36.0%	0.0%

[218] J. Heaton. *The Number of Hidden Layers*. 2017



(a) *Prediction error of UTS* (b) *Prediction error of E*

Figure 8.11 *Boxplots demonstrating average prediction errors for UTS and E from the generated Neural Networks*

The selection criterion for the neural network was principally for the smallest percentage error and smallest spread in errors. A secondary consideration was that under-prediction of performance was favoured when compared to over-prediction as the generation of an over-specified part is preferable. Because of this NN1 was selected for the capability profile. This was due to it having the mean absolute error nearest to zero (0.4% for UTS and 0.4% for E) and the smallest SD for both UTS and E (8.1% and 5/1% respectively). The spreads of these data are visualised in Figure 8.11 where NN1 can be seen to have the smallest spread in values. In addition to this, outliers showing large errors in UTS are underestimates and therefore preferable. These negative outliers are demonstrated in Figure 8.11a.

The structure of the selected neural network NN1 is depicted in Figure 8.12. The associated synapse weights are shown in Table 9.1.

To demonstrate the performance of the generated neural network we can compare the predicted vs. actual values for samples used in its generation. These are shown in Figure 8.13. Figure 8.13a shows predicted vs. actual values for UTS and Figure 8.13b for Elastic Modulus. It can be seen that there are no significant outliers with large differences in predicted vs. actual values showing that training, test and holdout samples were all predicted accurately by the neural

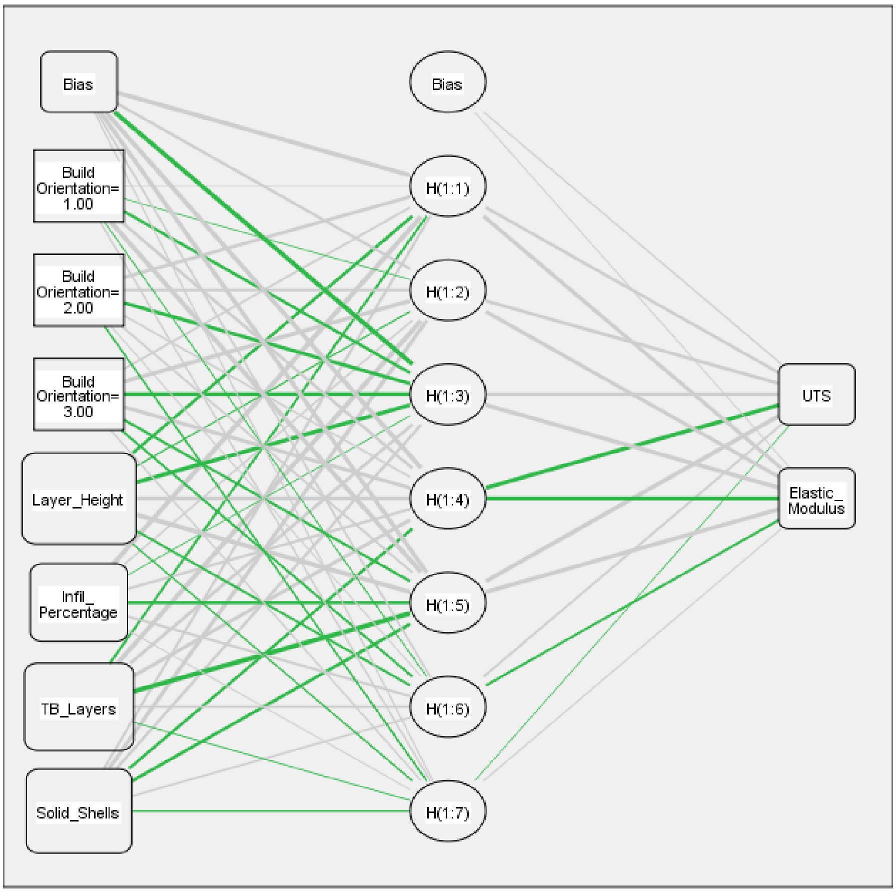
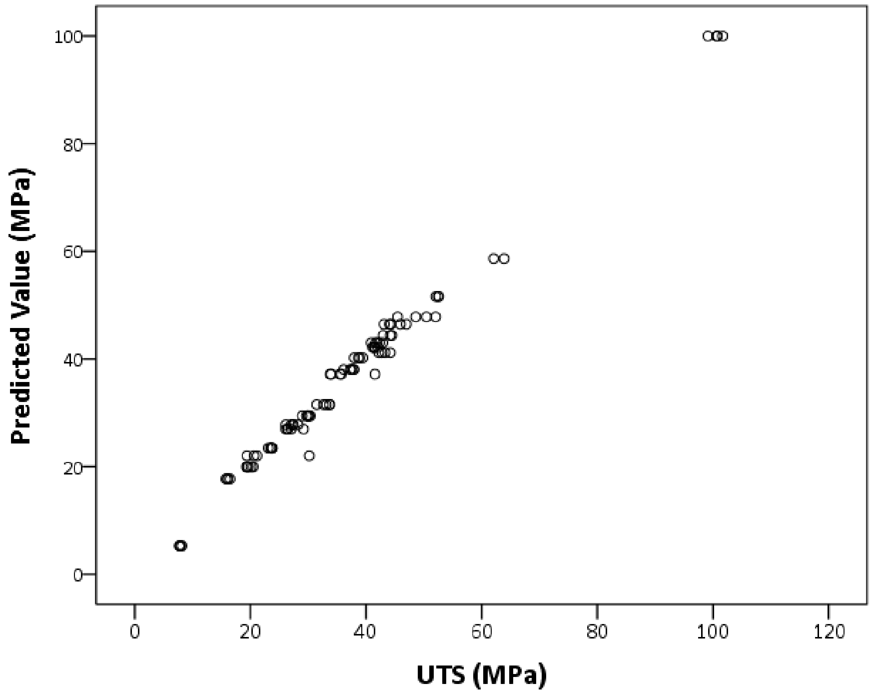


Figure 8.12 *Structure of Neural Network. Green lines indicate synapse weights greater than one, grey lines indicate weights of less than 1.*

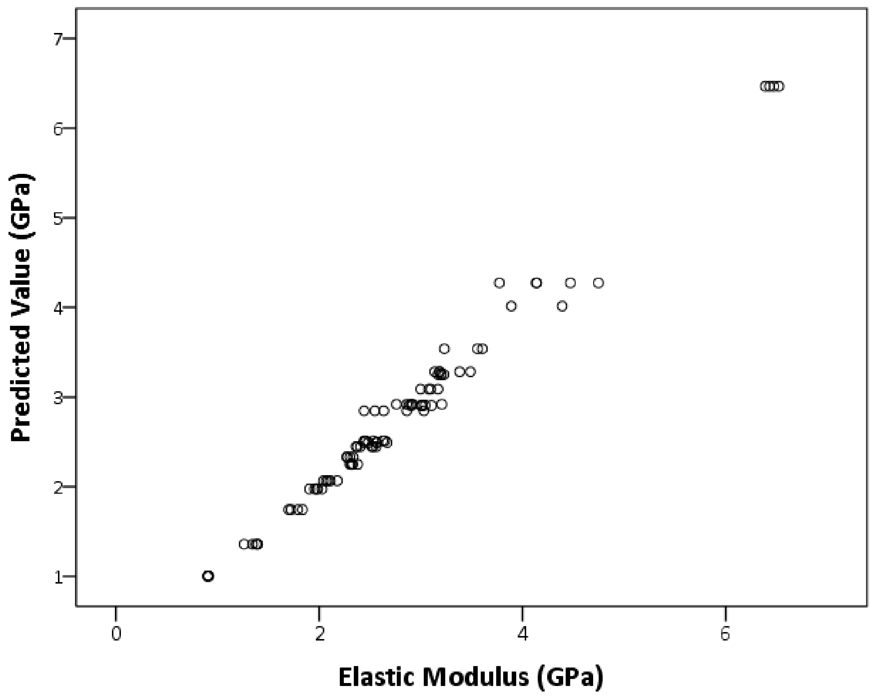
network. Residual error of the predicted values are shown in Figure 8.14. The maximum error can observed to be 7.5 MPa for UTS in Figure 8.13a, and 0.5 GPa for Elastic Modulus in Figure 8.13b.

Table 8.9 *Values for synapses of neural network corresponding to Figure 8.12*

Predictor		Hidden Layer 1							Output Layer	
		H(1:1)	H(1:2)	H(1:3)	H(1:4)	H(1:5)	H(1:6)	H(1:7)	UTS	Elastic_Modulus
Input Layer	**(Bias)**	1.628	0.668	-1.700	1.831	1.543	0.256	0.166		
	[BuildOrientation=1.00]	0.062	-0.031	-0.740	0.758	2.030	-0.132	0.203		
	[BuildOrientation=2.00]	0.979	0.663	-0.994	0.218	0.366	0.155	-0.246		
	[BuildOrientation=3.00]	0.257	1.317	-1.052	1.128	-0.556	-0.481	0.198		
	Layer_Height	-0.799	-0.157	-1.248	1.189	1.865	-0.492	-0.193		
	Infil_Percentage	2.633	0.210	-0.060	0.658	-0.903	0.505	0.141		
	TB_Layers	-0.497	2.245	0.861	1.009	-2.314	0.306	-0.063		
	Solid_Shells	0.618	1.239	0.706	-0.709	-0.847	0.250	-0.190		
Hidden Layer 1	**(Bias)**								0.188	0.115
	H(1:1)								0.784	1.224
	H(1:2)								0.944	1.174
	H(1:3)								0.993	1.317
	H(1:4)								-1.278	-1.205
	H(1:5)								1.387	1.343
	H(1:6)								0.402	-0.494
	H(1:7)								-0.026	0.155

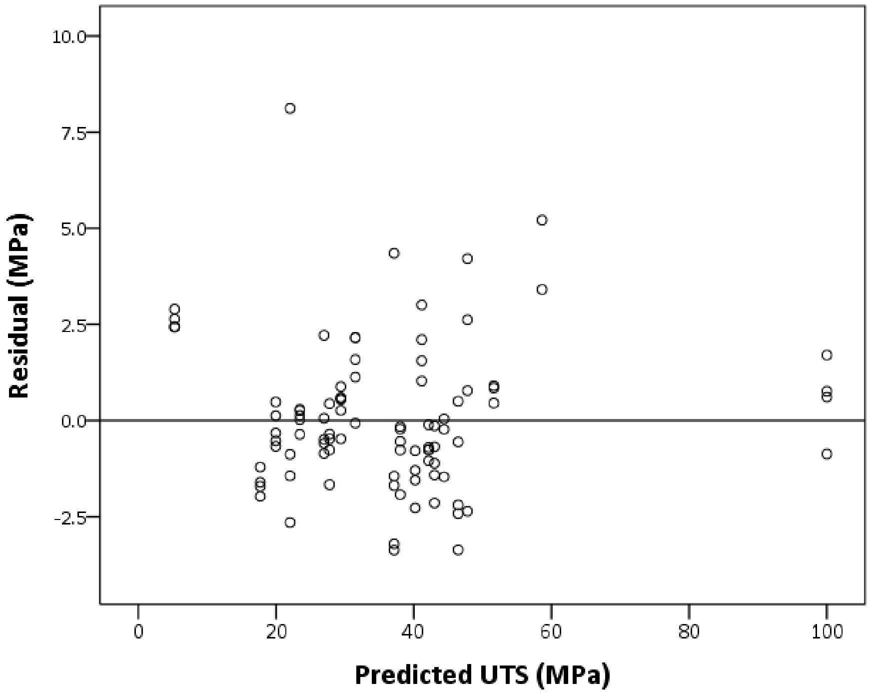


(a) *Graph demonstrating predicted vs. actual UTS*

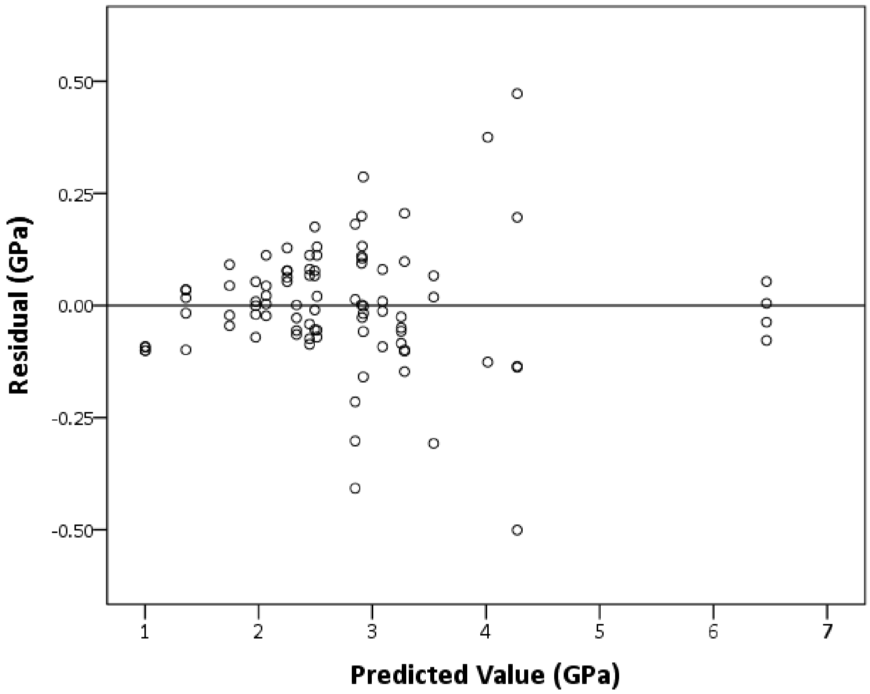


(b) *Graph demonstrating predicted vs. actual E*

Figure 8.13 *Graphs demonstrating actual values vs. those predicted by the neural network.*



(a) *Graph demonstrating residual of prediction for UTS.*



(b) *Graph demonstrating residual of prediction for E.*

Figure 8.14 *Graphs demonstrating residual errors of neural network.*

8.10 Discussion

The use of neural networks to form the capability profile has a number of advantages and potential drawbacks. As already mentioned, they are able to detect all possible interactions between independent variables and detect possible interactions between these and as such, have been able to generate a capability profile for FDM. A key limitation to this is that neural networks cannot predict reliably if extrapolating beyond the training data used to form it [219]. When using the generated capability profile therefore, input manufacturing parameters should not greatly exceed those used in its generation. This is a limitation which must be considered during the CP's implementation so as to prevent inaccurate predictions.

8.11 Conclusion

This chapter has presented and demonstrated how capability profiles will be incorporated within the design methodology presented in Chapter 6. In doing this, the necessary parameters were identified and these were categorised in terms of those that influence a part's mechanical performance through directly impacting mechanical parameters, influencing post slice geometry or both.

To generate the data upon which a capability profile would be formed, experimental design was carried out using the Taguchi method. This defined the manufacturing parameters to be used in the generation of test samples. These were then manufactured and tested.

Multiple linear regression was attempted in order to generate a capability profile but was unsuccessful as the assumption of independence of observation was violated.

Because of this, neural networks were then used as an alternative means of capability profile generation. Four neural networks were generated using SPSS software, from which the best performing one was selected to be used as the capability profile that would be taken forwards.

The next chapter will implement this capability profile in the design of functional components in a number of use cases.

[219] A. Trask *et al. Neural arithmetic logic units.* (2018)

Chapter 9

Validation

An overview of the methodology to enable the democratisation of design has been presented in Chapter 6. Verification of the suitability of tools selected and identification of an appropriate metaheuristic was carried out in Chapter 7. Chapter 8 detailed the formation and functionality of a capability profile for FDM which underpins the methodology.

This chapter presents the full implementation of the design methodology and illustrates the democratisation of design via three use cases. These enable an appraisal of whether design democratisation has been achieved and, if it has, how. These two aspects enable the design methodology to be validated.

The structure of this chapter is as follows. First the requirements of validating the design methodology are presented. This allows clarification of what must be appraised in order to conclude that design democratisation has been achieved. Next, a general overview of the implementation of the methodology within Grasshopper is described. Following this, specific areas are defined in greater detail. These are:

- The implementation of the capability profile.
- The definition of the fitness function.
- The static mechanics equations that are used in the functional models.

To demonstrate the application of these, three use cases are presented. These are used to show if and how design democratisation has been achieved.

9.1 Validation of design methodology

The aim of the democratisation of design is to reduce the requisite skill level to design functional components in order to enable non-technical users to generate these for themselves. To determine if this has been achieved, validation of the methodology must be considered from two perspectives.

Firstly the methodology must enable the generation of functional parts. This can be assessed by manufacturing the parts generated and determining if they meet their requirements.

Secondly,the methodology must demand a lower difficulty level for a user than the CAD based approach characterised in Chapter 4. This will be assessed by logging the difficulty and categories of steps taken during the design process using the same method as in Chapter 4 where the FDM design process was characterised. This permits two difficulty comparisons to be made with respect to both Technical Ability (TA) and Technical Understanding (TU). First, with the original CAD based approach characterised in Chapter 4. This allows the extent to which difficulty reduction has been achieved to be determined. Second, a comparison can be made with the forecast difficulty of the methodology that is demonstrated in Chapter 6. This allows conclusion to be made as to how the implemented methodology compares to the ideal. Reasons for this can be explored and steps to further difficulty reduction can be identified.

9.2 Implementation overview

The overall generative process is shown in Figure 9.1. It acts as a closed loop system with each iteration building upon the last. The process continues either until improvement stagnates, or a specified number of steps are completed. The numbered steps in Figure 9.1 correspond to the following:

1. User inputs their required load or results from physical testing.
2. PSO algorithm generates a set of geometries and manufacturing parameters.
3. These are passed into the capability profile block.
4. And also to shape analysis block to calculate material usage.
5. The CP block outputs mechanical properties which are used for static analysis for the specific load case for the design.
6. Material usage is output to fitness function.
7. Load capability is output from the Load Case block.
8. Fitness function output is returned to the PSO which then generates the next set of points.
9. Once a satisfactory part is generated, geometries and manufacturing parameters are output for use in the structural parametric model.

A general instantiation of the methodology within Grasshopper is shown in Figure 9.2. Elements within Grasshopper are referred to as 'blocks'. These can perform functions or can be inputs or outputs. Figure 9.2 shows two user inputs for their load requirement and actual recorded load and seven outputs corresponding to part geometries and manufacturing parameters. The methodology contains 8 functional blocks. These will be explored in the following sections with respect to whether they are related to a specific manufacturing resource (Section 9.3), related to the analysis process for a specific design task (Section 9.4) or undertake the particle swarm optimisation (Section 9.2.1).

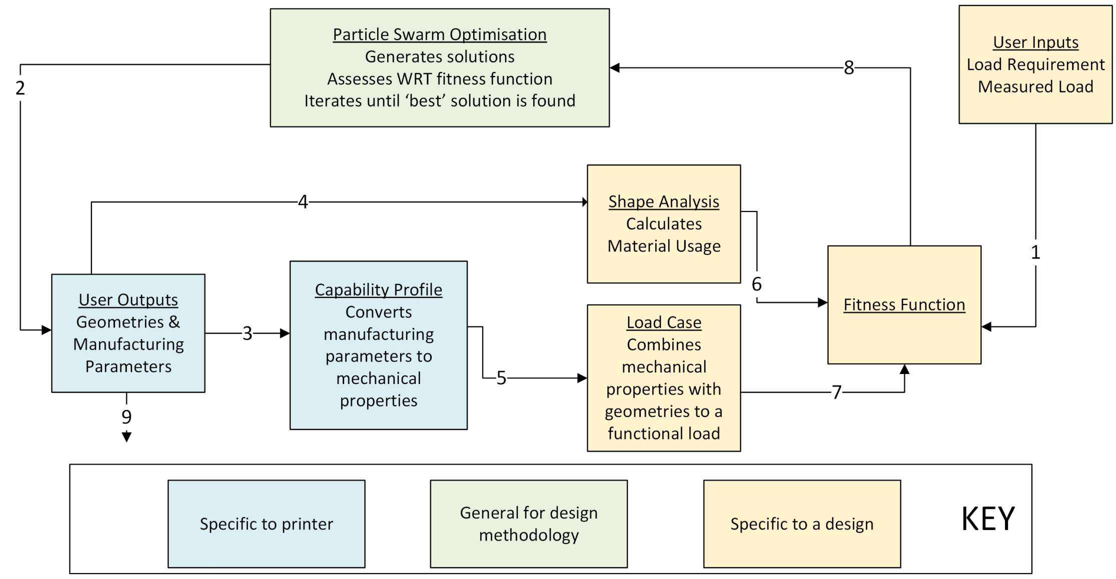


Figure 9.1 *Elements involved in the functional modelling within grasshopper*

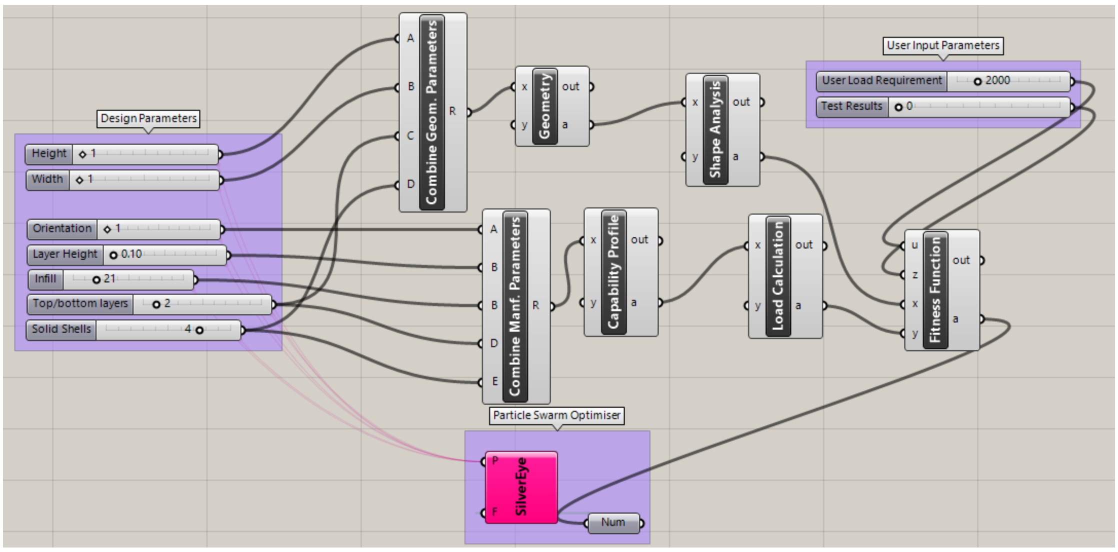


Figure 9.2 *Grasshopper implementation*

9.2.1 *Particle Swarm Optimisation*

The full implementation of the methodology uses particle swarm optimisation as it was found in Chapter 7 to be the best performing metaheurstic for navigating the FDM solution space. It receives two inputs. The first consists of the manufacturing and geometric parameters that it can vary. The second is the output from the fitness function (defined in Section 9.3.4). The PSO block is labelled Silvereye and the manner in which it is integrated within the overall methodology is shown in Figure 9.2.

9.3 Manufacturing resource specific blocks

The User Outputs and Capability Profile blocks are specific to an individual manufacturing resource. As the use cases are carried out on an individual FDM printer, the manufacturing resource is the same. As such, the same blocks will be used in all use cases. The manner in which user inputs are incorporated will also be considered.

9.3.1 User Outputs

The user outputs consist of the manufacturing parameters that will be generated in addition to requisite dimensions. These are shown in Figure 9.3.

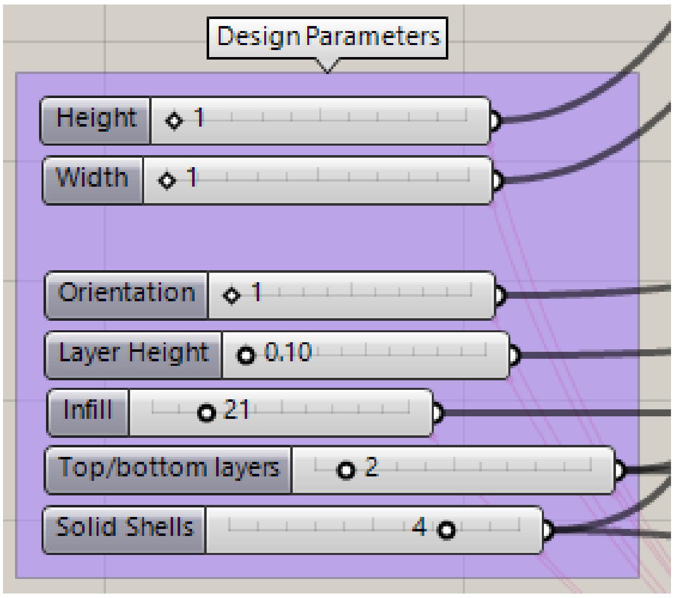


Figure 9.3 *Generated manufacturing and geometric outputs*

9.3.2 User inputs

To input their part requirements, the user must use the input sliders as shown in Figure 9.8. Additional inputs are necessary for any geometric constraints. These are bespoke to each individual use case.

9.3.3 Capability Profile

This section describes the underlying equations used to represent the capability profile. In Appendix B the implemented Python code for these sections can be found.

The synapse weights for the neural network used as the capability profile are shown in Table 9.1. To implement the neural network in python, the weights of

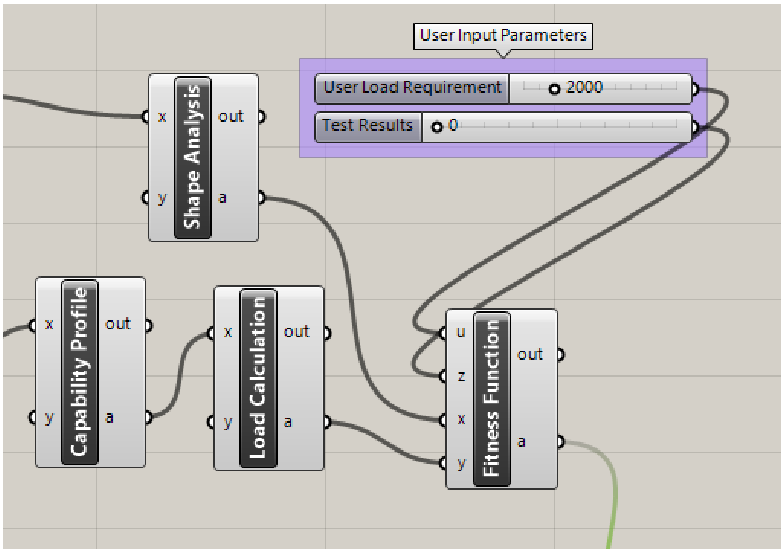


Figure 9.4 *User input sliders*

the synapses corresponding to the hidden and output layers of the neural network are represented in arrays B and E as shown in Equation (9.1).

Table 9.1 *Values for synapses of neural network*

Predictor		Hidden Layer 1							Output Layer	
		H(1:1)	H(1:2)	H(1:3)	H(1:4)	H(1:5)	H(1:6)	H(1:7)	UTS	Elastic_Modulus
Input Layer	(Bias)	1.628	0.668	-1.700	1.831	1.543	0.256	0.166		
	[BuildOrientation=1.00]	0.062	-0.031	-0.740	0.758	2.030	-0.132	0.203		
	[BuildOrientation=2.00]	0.979	0.663	-0.994	0.218	0.366	0.155	-0.246		
	[BuildOrientation=3.00]	0.257	1.317	-1.052	1.128	-0.556	-0.481	0.198		
	Layer_Height	-0.799	-0.157	-1.248	1.189	1.865	-0.492	-0.193		
	Infil_Percentage	2.633	0.210	-0.060	0.658	-0.903	0.505	0.141		
	TB_Layers	-0.497	2.245	0.861	1.009	-2.314	0.306	-0.063		
	Solid_Shells	0.618	1.239	0.706	-0.709	-0.847	0.250	-0.190		
Hidden Layer 1	(Bias)								0.188	0.115
	H(1:1)								0.784	1.224
	H(1:2)								0.944	1.174
	H(1:3)								0.993	1.317
	H(1:4)								-1.278	-1.205
	H(1:5)								1.387	1.343
	H(1:6)								0.402	-0.494
	H(1:7)								-0.026	0.155

$$B = \begin{pmatrix} H1:1_1, & H1:2_1, & \dots & H1:7_1 \\ \vdots & \vdots & & \vdots \\ H1:1_7, & H1:2_7, & \dots & H1:7_7 \end{pmatrix} O = \begin{pmatrix} UTS_1, & EM_2 \\ \vdots & \vdots \\ UTS_8 & EM_8 \end{pmatrix} \tag{9.1}$$

The capability profile receives manufacturing parameters as inputs. Continuous inputs first need to be normalised according to Equation (9.2)

$$x_{norm} = \frac{x - \bar{x}}{\sigma} \tag{9.2}$$

where x_{norm} is the normalised value of parameter x, $\bar{x}$ is mean x value and σ is the standard deviation. Build orientation is treated as a categoric variable and has three separate binary inputs (x, y, z) into the capability profile.

Once the input values are normalised they are formed into an input array A shown in Equation (9.3)

$$A = \begin{pmatrix} b, & x, & y, & z, & \upsilon, & \alpha, & \beta, & \omega \end{pmatrix} \tag{9.3}$$

Where b is bias and equal to a value of 1, x, y, z are binary inputs corresponding to build orientation, υ is layer height, α is infill percentage, β is top and bottom layer thickness and ω is the number of solid shells.

The first stage of the calculation process involves the hyperbolic tanh function being applied to the summed inputs and respective synapse weights to create C as shown in Equation (9.4).

$$C = \tanh\left(A \cdot B\right) \tag{9.4}$$

C is then prepended with a bias value of 1, forming D for the next phase of calculation.

Finally, UTS (σ) and E can subsequently be calculated by Equation (9.5). These are provided as outputs from the capability profile.

$$\begin{pmatrix} \sigma, & E \end{pmatrix} = D \cdot O \tag{9.5}$$

Where O corresponds to the values from the output layer of the neural network as defined in Equation (9.1).

9.3.4 Fitness Function

The fitness function from the initial implementation in chapter seven is expanded to permit better exploration of the solution space. Its basic function is to produce a part that can fulfil its required function by withstanding a given load with minimal material usage whilst also incorporating results from physical testing. The equation of the fitness function is show as Equation (9.6)

$$\phi = \frac{\psi L}{A_{mat}} \tag{9.6}$$

where ϕ is the fitness value to be maximised, ψ is the product of penalty multipliers and L is the required load and is equal to $Min(F_{target}, F_{required})$. F_{target} is the load the part needs to be able to take. $F_{required}$ is calculated according to Equation (9.7)

$$F_{required} = \tau F_{target} \tag{9.7}$$

Where τ is the Load Ratio and is calculated as $\frac{F_{target}}{F_{actual}}$. F_{actual} is a result from physical testing. F_{target} is the load that the part is required to take.

Penalty multipliers are implemented in order to:

- Ensure solutions generated are within the bounds of what the capability profile can generate.
- Ensure the dimensions generated are possible.
- Ensure the print is reliable.
- Direct the algorithm more quickly to a solution.

Eight penalty multipliers were incorporated with values of either 0.1 or 0.01, these are shown in Table 9.2.

Table 9.2 *Penalty multipliers incorporated in fitness function*

Penalty Multiplier	**Value**	**Decision**	**Explanation**
1	0.1	$UTS > 60MPa$	Applied if generated part has UTS outside of predictive capability of of CP
2	0.1	$TB > 2mm$	Applied if top & bottom layer thickness is below bounds of what the CP can predict
3	0.1	$SS > 2mm$	Applied if solid shell thickness is below bounds of what the CP can predict
4	0.1	$TB < 0.5mm$	Applied if top & bottom layer thickness is below bounds of what the CP can predict
5	0.1	$2 * SS >$ height	Applied if total solid shell thickness exceed part width
6	0.1	$2 * TB >$ thickness	Applied if top & bottom layer thickness exceed total part thickness
7	0.01	$Load < RequiredLoad$	Applied if predicted load is less than required load of the user
8	0.1	$Infill < 20\%$	Applied to avoid low infill that would yield an un-reliable print

9.4 Analysis approach

The functional models use mechanical properties defined by the capability profile and a static mechanics analysis of where the part is envisaged to fail.

This approach could be considered an extension to that presented by Umetani and Schmidt [220]. The authors develop a method that can identify weak points in designs and use this to recommend print orientations for parts. The static mechanics approach used in the following use cases goes further. Through combination with a capability profile it is able to recommend not only print orientation but a full suite of manufacturing parameters. Also, as the analysis is undertaken earlier in the design stage, weaknesses can be identified before the final design has been generated.

The analysis approach necessitates use of a number of load cases and shape analysis. These will be defined in the following sections.

[220] N. Umetani and R. Schmidt. *Cross-sectional structural analysis for 3D printing optimization.* (2013)

9.4.1 Load Cases

The analysis carried out in these use cases consist of a mixture of simple tension and compression calculations as well as applications of Euler-Bernoulli beam theory. The equations used for these are presented in the following sections.

9.4.1.1 Tensile

Tensile loading is calculated according to Equation (9.8).

$$F = \sigma A_{total} \tag{9.8}$$

Where F is a force in Newtons, A_{total} is the combined area of shell and infill in mm^2, σ is the ultimate tensile strength output by the capability profile in MPa.

9.4.1.2 Bending

Bending is described using Euler-Bernoulli beam theory. It can be used for straight beams and also curved beams where the cross section is small compared to the radius of curvature.

$$\sigma = \frac{My}{I} \tag{9.9}$$

Where σ is equal to the UTS, M is the applied moment, y is the distance to the neutral axis and I is the second moment of area calculated about the netrual axis.

9.4.1.3 Compression

Specimens loaded under compression can either fail purely through compression or buckling.

$$F = \sigma \cdot A_{total} \tag{9.10}$$

Where F is the maximum force, σ is compressive strength and A_{total} is the smaller of either the area of the applied load or cross section of the specimen itself. Compressive strength for 3D printed parts is shown to be around a fifth of tensile strength [221] and is calculated accordingly.

[221] R Hernandez *et al. Analyzing the Tensile, Compressive, and Flexural Properties of 3D Printed ABS P430 Plastic Based on Printing Orientation Using Fused Deposition Modeling.* (2016)

9.4.2 Shape Analysis

Shape analysis calculates areas of both shell and infill. It also permits the calculation of solid material at the cross section (A_{mat}) as per Equation (9.11)

$$A_{mat} = A_{shell} + \alpha A_{infill} \tag{9.11}$$

where A_x corresponds to shell and infill areas respectively and α is the percentage infill.

Second moment of area is calculated in a similar manner as shown in Equation (9.12)

$$I_{tot} = I_{shell} + \alpha I_{infill} \tag{9.12}$$

where I is the second moment of area.

9.5 Selected use cases

Three use cases were selected to demonstrate the methodology. These were selected in order to represent three loading scenarios of tension, compression and bending.

The generation of a tensile test dog-bone specimen to withstand a required load was used as the tensile use case. Whilst notably lacking in originality following the testing carried out in the generation of a capability profile, a dog bone specimen can be tested easily in a tensile test machine. In this way it allows a thorough assessment of the generated specimen under controlled conditions. This use case is shown in Figure 9.5a

The remainder of the use cases were items taken from the design repository Thingiverse. Using these as use cases enables the methodology to be applied in its intended environment, albeit via means of a human actuated instantiation.

To test bending, an S-hook was chosen and is shown in Figure 9.5b. A number of S-hooks exist in Thingiverse including S-hook for holding IV fluid that is implemented and used in the field by Field Ready [222] as shown in their parts catalogue [223]. For a specimen under a compressive load a table riser was selected (shown in Figure 9.5c).

[222] Field Ready. *IV Bag Hook*. 2016
[223] Field Ready. *Parts catalogue*. 2018

(a) *Tensile Use case*

(b) *Bending use case*

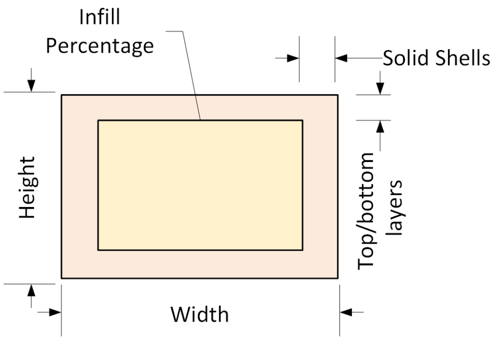
(c) *Compressive use case*

Figure 9.5 *Generated parts for implementation of design methodology*

9.5.1 Tensile Specimen

The aim of this use case was to generate a test specimen with a rectangular cross section that could withstand a tensile load of 1.5kN. The generative specimen is demonstrated in Figure 9.6a.

(a) *Generative tensile specimen.*



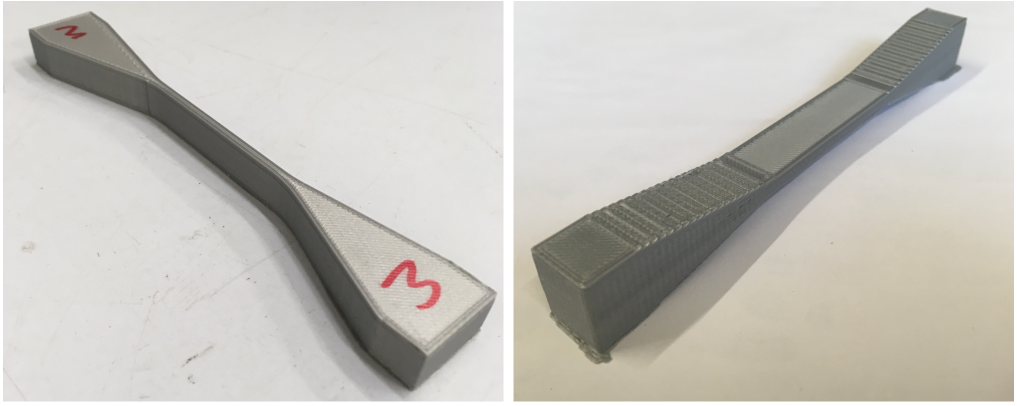
(b) *Tensile cross section demonstrating variable parameters.*

Figure 9.6 *Generative tensile sample and variables for optimisation*

The parameters that could be varied in its generation are demonstrated in Figure 9.6b. In addition to these build orientation could also be varied. Testing was carried out in accordance with the methodology used to generate the capability profile in Chapter 8 and took place after each iteration of the design. The results can be seen in Table 9.3. The first generated sample is shown in Figure 9.7a and the final sample in Figure 9.7b.

The functional model for this use case employed the Tensile equation as defined in Equation (9.8).

To reach a specimen that was able to meet the functional requirement, three generations were necessary. It can be seen that on average specimens generated perform at roughly 56% of what is predicted.



(a) *First iteration generated specimen* (b) *Final iteration generated specimen*

Figure 9.7 *Generated parts for tensile load case*

Table 9.3 *Outputs from each iteration in the tensile test use case*

	Iteration		
Parameters	**1**	**2**	**3**
Build Orientation	X	X	Y
Height mm	11.1	5.3	13.3
Width mm	2.3	7.2	4
Infill $\%$	80	59	68
Solid shells	7	3	2
TB layers	7	8	5
Layer Height (mm)	0.22	0.17	0.3
Predicted Load (kN)	1.50	2.25	2.9
Actual Load (kN)	0.94	1.15	1.61
Ratio of Actual/Predicted (kN)	0.63	0.51	0.56

9.5.2 S-Hook

The aim of this use case was to generate an S-hook that can accommodate a load of 150N. This load is based upon the recommended loading of ten times the weight of an IV bag as described in by Field Ready [222]. The user is required to input their load requirement and also radii of upper and lower hooks. A parametrised version of this hook is shown in Figure 9.8. In this use case, print orientation is pre-selected as only with the hook flat on the bed can it be reliably printed. As a results there is one fewer degree of freedom in this use case than in the tensile use case.

The functional model in this cases is based upon Euler-Bernoulli beam theory

[222] Field Ready. *IV Bag Hook*. 2016

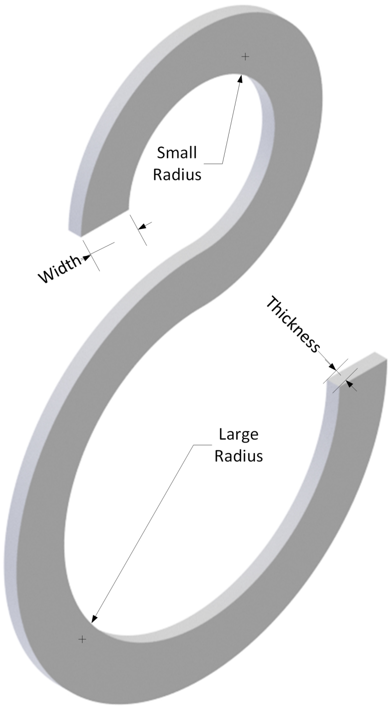


Figure 9.8 *Parametrised hook showing dimensions. Radii are input by the user, width and thickness are generated*

as shown in Equation (9.9). Describing the part of a curved beam in this way is valid as the radius of curvature is large compared to the cross section. Testing of these hooks is shown in Figure 9.9a and Figure 9.9b.

Results from the iterations are shown in Table 9.4. Through use of the methodology a part able to meet requirements was designed in just two generations. As in the tensile use case, a consistent ratio of 0.86 for actual to predicted load can be observed.

(a) *First hook supporting a load of 10kg.*

(b) *Final hook supporting required load of 15kg.*

Figure 9.9 *Generated hooks under testing*

9.5.3 Table-riser

A table riser was selected as a compressive use case for the design methodology. Fewer inputs were generated in this use case as print orientation was predetermined, outer radius of the riser is input by the user along with the magnitude and radius of the applied load. Outer radius was 16mm and the radius of the applied load is 14mm. These parameters are shown in Figure 9.10. The aim of this use case was to generate a 20mm high table riser that could sustain a maximum compressive load of 4kN. This load represents and actual load of 400N with a 10 times safety factor.

Manufactured parts were validated through compression testing on a 25kN Instron test machine. A picture of a generated sample mid-test is shown in Figure 9.11.

As well as demonstrating the functionality of the methodology, this use-case also permits assessment of the capability profile's limitations. The CP was generated with experimental data from tensile tests - this use case allows elucidation as to whether it can be extended to compressive use cases also. The results of the parts generated are shown in Table 9.5. A successful table riser is generated after 3 generations. It can again be observed that a consistent ratio of actual to predicted loads of around 0.75 is apparent in this use case.

Table 9.4 *Outputs from each iteration of S-hook generation*

	Iteration	
Parameters	**1**	**2**
Build Orientation	X	X
Height mm	4	4
Width mm	15	15
Infill $\%$	79	81
Solid shells	2	4
TB layers	6	6
Layer Height (mm**)**	0.3	0.3
Predicted Load (N**)**	150	173.9
Actual Load (N)	130	150
Ratio of Actual/Predicted	0.867	0.863

Though an appropriate part was generated. More testing is required to deduce whether the capability profile can be reliably applied to other compressive use cases.

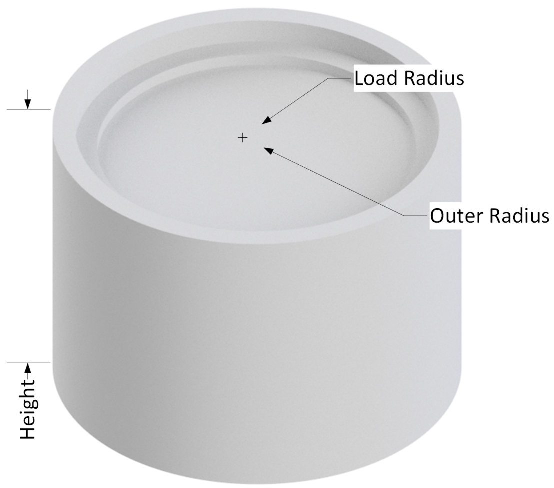


Figure 9.10 *Parametrised table riser showing user input dimensions*

Figure 9.11 *Compressive testing of table riser*

Table 9.5 *Results of generated table risers*

Parameters	**Iteration** 1	2	3
Build Orientation	Z	Z	Y
Infill %	21	21	21
Solid shells	5	7	2
TB layers	3	3	11
Layer Height (mm)	0.23	0.21	0.10
Predicted Load (kN)	4.2	5.2	5.8
Actual Load (kN)	3.4	3.8	4.5
Ratio of Actual/Predicted	0.8	0.73	0.78

9.6 Discussion

The purpose of this chapter is to validate that the created design methodology can enable the democratisation of design. The methodology's ability to do this can be demonstrated in two different ways. Firstly by it being able to generate functional components, and secondly by reducing the difficulty of the design process. The following sections will explore both of these by identifying whether the methodology is valid and if difficulty in the design process is reduced. The conclusions of these will be used to determine whether the research questions of this thesis have been met in the following discussion chapter.

9.6.1 Generation of functional components

All three use cases have demonstrated the generation of functional load bearing components for manufacture via FDM. The realisation of a functional part took at most three iterations, with the S-hook requiring only two. From this it can be concluded that the design approach presented in this thesis is valid. The combination of capability profiling with multiple design iterations incorporating physical testing results have enabled the generation of functional components.

9.6.2 Difficulty reduction

The quantification of difficulty reduction is essential in determining whether or not design democratisation has been achieved. Table 9.6 demonstrates the difficulty levels that were assigned in the characterisation of the FDM design process in Chapter 4. These difficulty levels are assigned to each step in the design process and are used to determine the extent to which difficulty in the design process has been reduced for the three use cases. Design steps are again categorised as follows:

- **Software Interaction** - e.g. opening a program, saving a part or exporting a file.
- **Hardware Interaction** - e.g. operating a 3D printer.
- **Decision** - e.g. choosing a course of action, deciding how to use the software to achieve a goal.
- **Observation/Measurement** - e.g. testing an item or identifying features on an existing object
- **Geometry alteration** - generating or changing 2D or 3D geometry.

With design steps categorised and assigned difficulty levels, comparisons are made between the initial CAD based process (Chapter 4), the predicted performance of the design methodology (Chapter 6) and its actual performance as demonstrated in this chapter.

A number of figures are used to demonstrate this. Table 9.7 illustrates the reduction in difficulty for each category of design step with a heat map. It shows the difficulty associated with the five categories of design steps and the respective difference between the traditional and democratised methodologies. Figure 9.12 demonstrates the reduction in quantity of design steps between the traditional CAD based process, predicted process and the actual implementation of the design methodology. Figure 9.13 compares the cumulative difficulty in terms of ability and understanding for each design approach cumulatively and each iteration individually.

Through use of the design methodology, the steps a user is required to take are reduced by a third when compared to the traditional CAD based approach (shown in Figure 9.12). The cumulative difficulty of these steps can also be seen to be reduced by the same amount (shown in Figure 9.13).

These significant reductions in number of steps and in difficulty can be attributed to two key areas. First, geometry modification steps can be seen to be removed completely (shown in Figure 9.12). As such, the difficulty for this can be seen to be reduced from 3 to 0 for both ability and understanding (shown in Table 9.7). Second, decision making steps are reduced from 40 to 6 (shown in Figure 9.12). Because of this, the level of difficulty is reduced from 3.3 to 2.2 for understanding and 3 to 0 for ability. This shows how the system takes design decisions on behalf of the user. This is demonstrated by the reduction is decision steps that need to be taken by the user.

In all design categories the number of steps were reduced (shown in Figure 9.12) with difficulty also reduced or left the same for (shown in Table 9.7. Despite this, there are a few areas in which the actual implementation of the methodology does not perform as well as it was predicted to. These areas are highlighted in Table 9.7 and are understanding for observation and measurement (where difficulty is 0.7 points higher), and understanding in decision making (where difficulty is 0.5 points higher). These can be attributed respectively to the elucidation of the requirements of the part pre-design and checking that the generated part is actually able to meet its requirements. Exploration as to how these steps could be removed and thus achieve further design democratisation will be considered in the discussion chapter.

Table 9.6 *Definitions of defined difficulties. Design difficulty is a function of technical ability and understanding.*

Difficulty level	**Description**	**Technical Ability Example**	**Technical Understanding Example**
0	Not relevant to task	-	Change a dimension
1	Requires everyday knowledge	Open Autodesk Inventor	Identify what bracket needs to fit to
2	-	Open existing sketch	Elicit how a hook will hang an item
3	Requires technical knowledge that could be learned through hands on experience	Apply fillet to corner	Identify measurements that are required for design
4	-	Use inventor offset function	Decide shape profile to minimise stress concentrations
5	Requires knowledge that was taught in engineering degree	Edit thread profile to better suit requirements	Decide strategy to reduce deflection under load

Table 9.7 *Difficulty scores for types of tasks within design methodology*

	Software Interaction		Hardware Interaction		Observation & measurement		Decision		Geometry		TOTAL	
	A	U	A	U	A	U	A	U	A	U	A	U
CAD based Hook	1.7	3.0	2.0	0.0	1.7	2.9	3.0	3.3	2.3	3.0	2.1	3.2
Predicted Hook	1.4	1.3	1.0	0.0	1.8	1.0	0.0	1.7	0.0	0.0	1.4	1.4
Actual Hook	1.2	1.3	1.0	0.0	1.7	1.7	0.0	2.2	0.0	0.0	1.3	1.8
Difference CAD v Predicted	-0.3	-1.7	-1.0	0.0	0.1	-1.9	-3.0	-1.6	-2.3	-3.0	-0.7	-1.8
Difference CAD v Actual	-0.5	-1.8	-1.0	0.0	0.0	-1.2	-3.0	-1.1	-2.3	-3.0	-0.8	-1.5
Difference Actual v Predicted	-0.2	-0.1	0.0	0.0	-0.1	0.7	0.0	0.5	0.0	0.0	-0.2	0.4

Figure 9.12 *Number of steps in each category for design task*

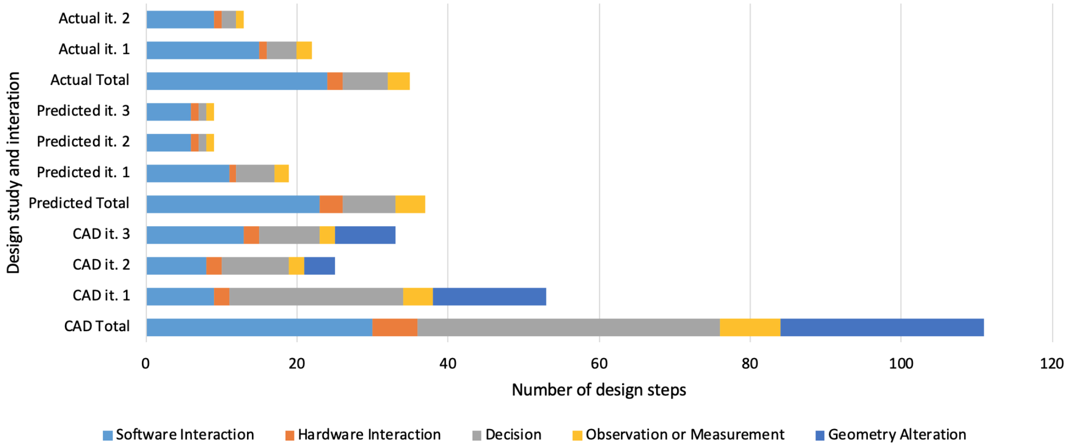
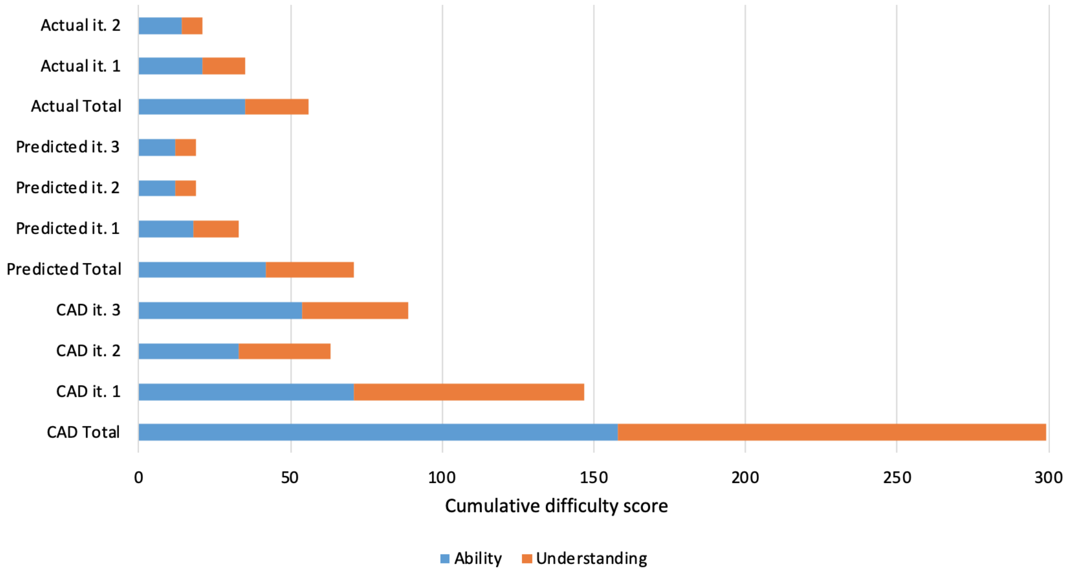


Figure 9.13 *Comparison of difficulty for ability and understanding*



9.6.3 Iterative hierarchy

Section 4 of Chapter 6 considered a number of opportunities for design learning that followed Confuscius' methods of acquiring wisdom (experience, imitation and reflection) and in doing this mirrored an existing concept known as communities of practice.

Initial use of the design methodology requires learning by experience. This is shown in the use cases as each builds on the information provided by each design iteration.

Elements of learning by imitation are demonstrated in the three use cases presented in the form of the ratios of actual vs. predicted behaviour. In all use cases these are shown to be consistent across iterations. As such, if a user were to design another of the same component as in the use cases, this ratio could be used to reach a solution more quickly.

Learning by reflection would involve the application of these design learnings to different design tasks. For example, the findings of the S-hook use case could be applied to another design task that was modelled using Euler-Bernoulli beam theory. Exploration into how this could be achieved will be commented upon in further work.

9.7 Conclusion

This chapter has presented a validation of the design methodology developed in this thesis. In doing this, individual instances of design democratisation have been demonstrated in three separate use cases. All enabled the generation of functional components for manufacture via FDM without any need for the user to have detailed knowledge of design, static mechanics or FDM. The number of steps required to produce a functional part are reduced by a third, and the the difficulty in completing these steps is also shown to be reduced by the same amount.

The following discussion chapter will address the generalisability of these results, determine whether the research questions and aim of the thesis have been achieved and consider how wider implementation of this methodology could be enabled.

Chapter 10

Discussion

This chapter discusses the research presented in the previous chapters of this thesis. It seeks to answer the following questions:

- Has the thesis aim been met?
- How can the work presented in the thesis be generalised?
- What are the next steps for the research that has been carried out?
- How can proliferation of FDM and other 3D printing techniques be increased?

The following sections address each of these points, starting with consideration as to if and how the thesis aim has been met. To achieve the aim set out in Chapter 1, three Research Questions (RQs) are formulated. The methods employed in addressing each of these, an appraisal of their limitations along with a summary of their respective findings are considered in Section 10.1.

Next the generalisability of the research will be considered. In this thesis a design methodology capable of enabling the democratisation of design is developed and implemented for a number of use cases. This section considers whether the findings from these select use cases can be applied more generally.

Following discussion of the generalisability of results, steps to be taken in the continuation of the research are outlined. These include additional user testing to enable further validation that the proposed methodology enables the democratisation of design, partnering with a design repository provider to investigate how the methodology could be implemented within this environment.

The final section of the Discussion re-examines the arguments made for design democratisation in the Introduction to this thesis. These arguments were based upon a wide range of literature that expelled the benefits that manufacturing paradigms based upon additive manufacture would enable., including how it could be an empowering tool for development by providing affordable manufacturing capacity. From the findings of this thesis, a re-examination of these is carried out along with an assessment of the progress that this thesis makes towards the proliferation of consumer 3D printing.

10.1 Fulfilment of Aim

The primary area for discussion is that of the fulfilment of the thesis aim. This was stated at the end of Chapter 1 as:

> To create a design methodology to enable the democratisation of design for FDM.

The aim was met through the development, implementation and evaluation of a design methodology that could enable the democratisation of design. This allowed non-technical users to develop functional parts for themselves without any pre-requisite knowledge of the use of CAD tools, static mechanics or FDM printing. Its implementation enabled a great reduction in both the quantity of design steps that needed to be undertaken and also the difficulty level of these steps in terms of both technical understanding and ability.

Implementation and evaluation of the design methodology alone was not enough to fulfil the research aim. In Chapter 3, this was broken down into three research questions corresponding to Blessing & Chakrabarti's Design Research Methodology (DRM). These research questions included:

1. What are the requirements of the democratisation of design for FDM?
2. How can generative design approaches be used to augment the existing capabilities of design platforms?
3. How is design democratised by incorporating a generative design approach into existing design platforms?

The following sections will consider how each of these research questions was addressed.

10.1.1 Research Question 1

The first research question was:

RQ 1 - What are the requirements of the democratisation of design for FDM?

This corresponded to the Descriptive 1 stage of the DRM used to frame the research carried out in this thesis. This research question was addressed in chapters 4 & 5 which respectively approached the requirements of design democratisation from two perspectives. Firstly from the perspective of the design capabilities of a prospective user, and secondly from the manufacturing resource capabilities of FDM. Addressing both of these areas was essential as the democratisation of design can be considered as facilitating communication and interaction between user and manufacturing resource. Understanding the limitations and requirements of each was therefore necessary before the requirements of an appropriate design methodology could be developed.

To identify the requirements for the democratisation of design for FDM from the perspective of a prospective user, a design study was undertaken that involved the author designing and manufacturing three different parts representa-

Table 10.1 *Key findings from work undertaken in addressing Research Question 1 and subsequent requirements of design methodology that can enable the democratisation of design*

	Key findings	**Requirement of design methodology**
1	Most difficulty in the design of parts for FDM is present in decision making and in observation and measurement.	Design methodology must be able to take reasoned design decisions on behalf of the user
2	FDM is highly variable process (up to 26%) and existing techniques are not able to satisfactorily predict properties of manufactured parts.	Design methodology must involve physical testing to validate the behaviour of manufactured parts.
3	Mechanical properties do not scale, and are affected by the shape of a part.	Design methodology must permit multiple iterations in order to enable the incorporation of physical testing results.

tive of the typical design challenges that parts manufactured via FDM seek to overcome. These studies involved the logging of all design steps undertaken, the categorisation of each step and an assignment of difficulty.

To identify the requirements of the democratisation of design for FDM from the perspective of the manufacturing process first a literature review was carried out to elicit existing knowledge surrounding the manufacturing process. From this review, a number of research gaps were highlighted and subsequently clarified via experimental testing. These were:

- The variability of the mechanical properties of parts manufactured via the FDM process.
- The respective effects of shape and scale on the the mechanical properties of parts manufactured via the FDM process.

The undertaking of both of these characterisations of the design and manufacturing processes for FDM permitted the elucidation of a number of key findings which were then used to frame the requirements of the design methodology. These are shown in Table 10.1.

In summary, RQ1 sought to elicit the requirements for the democratisation of design for FDM. This was carried out from both the perspectives of a prospective user and the manufacturing resource enabling the development of three requirements which have been demonstrated in Table 10.1. As such, it can be concluded that RQ1 was addressed successfully.

10.1.2 Research Question 2

The second research question was:

RQ 2 - How can generative design approaches be used to augment the existing capabilities of design platforms?

This research question corresponded to the Prescriptive phase of DRM and was addressed through the development of a design methodology. The requirements of this methodology consisted of those found when addressing RQ1 (shown in Table 10.1) and also the research gap identified in Chapter 2 - where it was posited that the capability of design platforms could be augmented through the incorporation of generative design approaches.

The development of the design methodology is described in chapters 6, 7 & 8. In each of these the theoretical framework corresponding to various elements of an appropriate design methodology were explored. When considered collectively they enabled the definition of how generative design approaches could be used to augment the existing capabilities of design platforms.

In chapter 6 the methodology was defined and explored from a number of perspectives that were as follows:

1. The envisaged interactions a user would need to take were outlined.
2. A functional system model was presented.
3. The necessary design representations were defined and their interactions explored.
4. Contextualised with respect to the Function Behaviour Structure (FBS) framework.

Points 2-4 allow the definition of how the design methodology functions, demonstrating how generative approaches can be used to augment the existing capabilities of design repositories. Point 1 permitted exploration of how design democratisation is achieved and gives an idea of the extent to which difficulty can be reduced through the use of the design methodology, thus validating it's prospective performance in advance of full implementation.

Chapter 7 consisted of a first implementation of the methodology to enable the selection of an appropriate toolset, and also means for navigating the solution space. The CAD package Rhino 6 was selected principally for it's Grasshopper parametric design add on and Particle Swarm Optimisation was found to be the most appropriate meta-heuristic for solution space navigation.

Capability Profiling (CP) is identified as a key enabling technology that underpins the functionality of the methodology. In Chapter 8 the interaction of a CP within the methodology is defined and extensive experimental testing results form its basis. Neural Networks are used to form a CP from these testing results.

Answering RQ2 required that a range of areas and perspectives be considered. These included defining the functionality of the design methodology and validating the tools that would be used in its implementation. Once all elements were defined and it was confirmed that the democratisation of design could be achieved through its use, a full implementation of the methodology could be undertaken.

By extensively defining the methodology from various perspectives, the ability of generative approaches to augment the existing capabilities were explicitly defined. Consequently, RQ2 can be considered to have been met.

10.1.3 Research Question 3

The final research question was:

RQ 3 - How is design democratised by incorporating a generative design approach into existing design platforms?

This required the full implementation of the methodology which was documented in chapter nine. Within this chapter three instances of the methodology in action were explored. These involved the development of the requisite functional and structural parametric models and their use to create components that could meet a designated behavioural requirement.

The implementation itself did not provide an answer to RQ3 directly, but provided a platform upon which a final design study could be carried out. To maintain consistency, for this design study the same approach as employed in Chapter 4 was used to characterise the democratised design approach. This permitted elucidation of the number, type and difficulty of all design steps a user needed to undertake in the development of a functional component.

The findings from this study demonstrated a two-thirds reduction in total number of steps and in cumulative difficulty of undertaking the design process. It also showed the total elimination of all geometry alteration steps and reduced the number of decisions the user needed to take from 40 to 7.

The substantial difficulty reduction enables the conclusion that the democratisation of design has been achieved. Moreover, the elimination of specific steps enable the conclusion that the mechanism enabling the democratisation of design is by the complete elimination of geometry alteration steps and substantial reduction in the and difficulty of design decisions that need to be undertaken. Because of this, through use of the methodology a user with no CAD experience, knowledge of static mechanics or of FDM printing is able to realise functional parts for themselves.

Correspondingly it can be concluded that RQ3 has been satisfactorily addressed. This is due to the evidence of the democratisation of design having been achieved and also the mechanisms that enable it.

10.1.4 Aim

In summary each research question contributed the following to the overall thesis aim:

- RQ1 enabled the requirements of the democratisation of design to be defined.
- RQ2 defined a methodology that could augment the capabilities of design platforms using a generative approach.
- RQ3 validated this methodology by quantifying how and to what extent the democratisation of design is achieved through its use.

By demonstrating that each of the thesis' research questions has been successfully met, in addition to the evidenced creation and implementation of a design methodology that is able to achieve the democratisation of design, it can be asserted that the aim has been fully met.

10.2 Generalisability

Whilst the thesis aim and research questions are shown to have been met. It is important to consider the generalisability of the techniques and results presented - can wider conclusions be drawn from the research presented in this thesis and, if not, what further work is necessary to enable this?

The following areas need to be considered with respect to the generalisability of the research presented:

- **Type of design task** - only load bearing components were instantiated as use cases.
- **Manufacturing resource** - the design methodology was only implemented for a single printer.

- **Only part of the design experience is considered** - the system interface was not developed.

The work undertaken in this thesis demonstrates the successful democratisation of design for load bearing components, for which the determination of whether a part is satisfactory or not is straight forward. It is binary in that they are either able to accommodate a given load, or they are not. Other types of design tasks are less straightforward. Fit type problems that involve for example interfacing components, will be more difficult as it is less clear whether a part is successful or not. In the case that it is not, it is unclear what would need to change in order to arrive at a satisfactory design. Achieving this would require a means of scanning the printed part to understand how it fails to meet requirements. Technologies exist for performing this sort of precision measurement but are yet to be incorporated into the prototyping or design process. Work is currently ongoing in trying to achieve within the design and manufacturing futures lab at the University of Bristol to achieve this [224]. In conclusion, generalisability of the methodology to other types of design tasks requires further work.

Related to the types of design tasks used to instantiate the design methodology is the extent to which the methodology (and implementations thereof) may reasonably be expected to capture all that is required to achieve high-performing outputs. This can largely be considered to be dependent upon the creation of a robust method to enable the generation of the general models that underpin the methodology. As such, this is outside of the scope of the research presented in the thesis, but will be commented upon in the subsequent further work section.

The functioning of the design methodology was underpinned by a Capability Profile (CP) of the FDM manufacturing process. A suitable CP was developed - but only for a single instance of a specific machine. Based on reviewed literature it is assumed that similar CPs would be able to be developed for other FDM printers and different additive manufacturing techniques. This supposition does however need to be validated by generating an additional functioning CP for another type of printer.

Related to both the type of design task and manufacturing resource is the generalisability of PSO algorithms and NNs used to instantiate the design methodology. Whilst specific instances of both of these are used, the expected differences in performance when applied to other design tasks can be considered small due to the optimisation still being about mechanical properties and load bearing behaviour of FDM components. As such, refinement of these, though potentially

[224] A. Nassehi. *Proto-twinning- what's it all about?* 2018

fruitful, is considered more towards marginal gains than significant improvement. Additionally, mechanical testing has a large impact on solutions generated, independent of the NNs or algorithms used. Moreover, the NNs are specific for an individual manufacturing resource and with the methodology as it stands, will be generated individually for each printer. The results demonstrated through the use PSO and NNs can therefore considered to be generalisable.

As is commented upon earlier in the thesis, the design process comprises of a number of different areas which contribute to difficulty. The design methodology has sought to remove difficulties associated with CAD, static mechanics and assignment of 3D printing parameters. In this way it can be considered that 'functional' design democratisation is enabled by the design methodology and has been demonstrated in its instantiation. For this reason it was not necessary to carry out testing with un-skilled participants as functional democratisation is shown by enabling the generation of functional parts and moving cognitive load from the user to design tool. The interface which permits a user to interact with a system is essential as even with difficulty from the aforementioned areas removed, a poorly designed interface will prevent a user interacting with the design tool effectively. Whilst this is essential in deploying a fully usable design tool, it was not central to thesis' aim and would need to be developed *in situ* within a design platform. As such, it can be considered that the outputs and results of the thesis remain perfectly valid. This, along with testing with un-skilled participants, will be considered in greater detail in the Further Work section.

10.2.1 Where's the expert?

The theme of this thesis is democratisation with the aim of enabling non-technical users to develop parts for themselves. However, as with any form of design democratisation, an expert is required somewhere in the process [225]. In the case of this methodology - an expert designer is required to develop the general models that would be hosted in the design library. This is not indifferent to the present situation with design repositories, where users upload their designs so other users may freely re-use them. Steps to enable this will be considered in the Further Work section.

[225] M. Goudswaard *et al. Different approaches to democratise design - are they equal?* (2019)

10.3 Future Work

A number of areas for further work have already been identified with respect to the generalisability of the results from the thesis. These will be commented upon here along with steps that need to be taken to permit further development of the design methodology.

To better frame these, the big vision for the research presented in the thesis will be explored. The further work steps can then be considered first steps in working towards this vision. Key areas that illustrate this vision are as follows:

- The design methodology would reach widespread use through deployment in a popular design platform such as Thingiverse.
- It would be applicable to a wide range of AM specific design tasks and a variety of different 3D printer makes and models.
- The entire CAD/CAM process would be cloud based and hosted within the design platform. A user would be able to undertake all elements of the design process including model selection and optimisation with the design tool then providing a G-Code output tailored to their individual requirements and manufacturing resource capability.
- Capability profiles would be available for different types of printers and would not need to be individually generated. These are adapted to the particularities of a user's printer through the manufacture and testing of functional parts.
- Design interventions can be made across types of design tasks and from the experiences of other users, not just from what is learned in the iterative process instantiated in this thesis.
- As design reasoning is embodied within the methodology, it is possible that it could be used as the basis for an educational tool. Instead of solely generating a satisfactory part, it could explain to the user the design rationale behind the part generated. In doing this it could enable users of the tool to understand how to generate functional 3D printed parts themselves.

The subsequent areas of further work can be considered steps towards the big vision highlighted above. Whilst they could be carried out individually, the following steps are ordered chronologically according to how further work could be carried out most effectively.

10.3.1 Further User testing

Difficulty reduction and subsequent design democratisation are both quantified through the undertaking of design tasks by the author of this thesis. Whilst this method of quantification was consistent with the earlier characterisation of the design process (in Chapter 4) further user testing is necessary in order to conclude fully that design democratisation has been achieved. As such, an avenue for further work is identified as undertaking further user testing.

10.3.2 Framework for the generation of models

In order for the method to function, expert designers are required to generate the general parametric and functional models that non-technical users require. This thesis has not considered the manner in which these would be generated but this is essential for enabling a practical implementation of the methodology. Further work might therefore consider the generation of a framework that expert designers would be able to follow in creating general structural and functional models.

10.3.3 Integration of method into design library

Research question two involved exploring how generative approaches could be used to augment the existing capabilities of design libraries. Following validation that the method is able to democratise design, embedding the approach into an existing design library is a logical next step. The work undertaken in this thesis constitutes a proof of concept which demonstrates that the design methodology can achieve design democratisation. Incorporating the methodology in a design library would also enable *in the field* testing, permitting elucidation of whether the design methodology is useful and practical in its envisaged environment.

10.3.3.1 Re-use of physical testing results

As noted at the end of Chapter 6, design learning takes place in the form of an iterative hierarchy aligned with Confucius' methods of acquiring wisdom. In Chapter 9 learning through experience and by imitation are demonstrated through the methodology. With further applications and more use cases, design learning can take place by reflection, with learning from different design tasks enabling the refinement of capability profiles and functional models.

10.4 FDM as an empowering tool for development

A final point of discussion regards the arguments that were taken to frame the thesis' aim and how these are impacted by the findings in the thesis.

A top down approach was used in Chapter one to frame the thesis aim. This guided why democratisation of design was important and the general techniques (ie generative approaches and design libraries) that could be brought together to enable it. This aim was then achieved via a bottom up approach in the analysis of the requirements and capabilities of envisaged users and manufacturing resources respectively. In this way, the design methodology developed in this thesis can be considered as a thread that attempts to link a global vision for FDM (top down) with an understanding of what it is really capable of (bottom up).

In doing this, a void was revealed between proponents of FDM who herald it as a tool that can enable high level societal change and what one can actually achieve with FDM. In cases, the former assumes both knowledge and capability of the latter that does not exist yet.

In 2011, 3D printing in general was on it's way to the peak of inflated expectation [226]. A more specific 3D printing hype cycle was published in 2015 which showed the 3D printing of consumable products at the innovation trigger level [227] and 5-10 years from maturity. Four years on from this, perhaps it now finds itself towards in the trough of disillusionment with with gaps between expected and actual capability becoming apparent. It is not all doom and gloom however, this is a normal cycle in technological development and all leads towards the plateau of productivity!

10.5 Conlcuding remarks

This chapter has discussed various aspects of the research undertaken and presented in this thesis. The following Conclusion chapter will bring the thesis to a close, summarising the research carried out, defining the contributions to knowledge and showing the publications achieved during the author's doctoral research.

[226] J. Fenn and H. LeHong. *Hype Cycle for Emerging Technologies, 2011.* (2011)
[227] Gartner. *Hype Cycle for 3D Printing.* (2015)

Chapter 11

Conclusion

To draw this thesis to a close, this chapter summarises the work presented in the thesis, and, from this, extracts its contributions to knowledge and evidences these with respect to publications generated during the research.

11.1 Summary of thesis

The aim of this thesis was to:

To create a design methodology to enable the democratisation of design for FDM.

This aim was developed in Chapter 1 which introduced additive manufacturing, in particular Filament Deposition Modelling, as a manufacturing technique that could provide significant sustainability and economic benefits over current mass manufacturing techniques. Whilst the manufacturing technology already exists and is both affordable and available to home users, what prevents further proliferation is a lack of availability of appropriate design tools. Because of this, it is proposed that by democratising design more widespread use of additive manufacturing technologies could be achieved.

Chapter 2 consists of a literature review that permitted the research aim to be refined into research questions. Existing approaches to the democratisation of design and technology were explored permitting the identification of possible technological solutions to the democratisation of design. From this, a research gap was identified in using generative design approaches to augment the existing capabilities of design repositories.

To address the identified research gap and the thesis aim, Chapter 3 defined the research framework of the thesis. After reviewing a number of research methodologies, Blessing & Chakrabarti's Design Research Methodology (DRM) was selected. Three research questions were subsequently proposed that aligned to the descriptive 1, prescriptive and descriptive 2 stages of DRM respectively. These are shown in Table 11.1

In Chapter 4 an existing CAD based process to design functional components for FDM was characterised in order to identify where difficulty currently exists for a user. From the results of this, the first requirement of a methodology able to achieve the democratisation of design is elucidated and requires that a methodology must be able to take reasoned design decisions on behalf of a user.

Chapter 5 detailed the characterisation of the FDM manufacturing process in order to understand its existing capabilities to ensure that the design method-

Table 11.1 *DRM stages with their corresponding research questions*

DRM Stage	Research Question
Descriptive I	**RQ1** — *What are the requirements of the democratisation of design for FDM*
Prescriptive I	**RQ2** — *How can generative design approaches be used to augment the existing capabilities of design platforms?*
Descriptive II	**RQ3** — *How is design democratised by incorporating a generative design approach into existing design platforms?*

ology would be compatible. Within this chapter existing literature surrounding the manufacturing process was reviewed and experimental testing was carried out to define any properties that were not available in existing literature. From this and experimental testing it was found that variability in UTS of identical specimens could vary by up to 26%, that these properties do not scale linearly and that they are affected by the shape of a specimen. From these results, two further requirements of the methodology were formulated including that it must incorporate physical testing to validate the performance of a designed part, and permit multiple design iterations in order to allow testing results to be incorporated.

Chapter 6 presented a platform agnostic overview of an iterative nine-step design methodology that could meed the requirements of design democratisation identified in the earlier chapters. The proposed methodology involved parametric models that enabled functional modelling of a component and the subsequent generation of geometric and manufacturing parameters. The predicted user interactions with the methodology were presented and characterised in the same manner as in Chapter 4. This permitted an indication of the potential level of design democratisation that could be achieved by the methodology. Capability profiling was defined as a key underpinning technology for the design methodology.

Chapter 7 detailed a first implementation of the methodology that enabled the verification of a suitable toolset for its deployment, and strategy for navigating the FDM solution space. The CAD package used was Rhino 6 which was selected for its Grasshopper parametric design add-on. In the Grasshopper environment the Universal Hook Generator was instantiated, enabling the assessment of three metaheuristic algorithms with respect to the speed and consistency of solutions they could generate. Particle Swarm Optimisation was found to most consistently generate feasible solutions.

In Chapter 8 the functionality of an FDM capability profile was defined and contrasted with those that are implemented in traditional manufacturing processes. Experimental testing was undertaken to form the capability profile. Neural-networks were used to generate a Capability Profile that was able to adequately predict the mechanical properties of generated parts with a mean accuracy of 0.4%.

Chapter 9 detailed the full implementation of the design methodology where three use cases were used to validate its functionality. Compressive, tensile and flexural user cases were selected. This chapter enabled a full run-down of how the methodology was implemented, detailing the creation of functional and structural models, along with the incorporation of the CP within the Grasshopper environment. Through characterisation of the methodology, a two thirds reduction in difficulty and in number of steps was observed. All geometry alteration steps were removed and design decisions reduced from 40 to 7. This observed reduction in difficulty permitted the conclusion that the democratisation of design had been achieved and the identification of the mechanism that enabled it.

In Chapter 10 the findings of the thesis were discussed. It was concluded that via means of satisfactorily addressing each of the three research questions, that the thesis aim of *creating a methodology that could enable the democratisation of design for FDM* had been achieved. In addition to this, the generalisability of the thesis' findings were explained and avenues for further work were developed.

The work presented within these summarised chapters represents a number of contributions to knowledge. These will be outlined and evidenced in the following section.

11.2 Contributions to knowledge

The research undertaken in this thesis constitutes four principal contributions to knowledge. These are:

- The development of a new design methodology that can permit the democratisation of design.
- The elucidation of requirements for the democratisation of design.
- The creation of new knowledge regarding the FDM process.
- The development and use of a capability profile for FDM.

Each contribution will be explored in the followings sections.

11.2.1 Hybrid virtual-physical design methodology

The principal contribution to knowledge in this thesis is the development and implementation of a new methodology that can enable the democratisation of design for FDM. Achieving this was the principle aim of the thesis and explanation as to how this was achieved was detailed in the discussion chapter. The manner in which this forms a contribution to knowledge can be considered in both general and specific terms.

In a more general sense, a design methodology that can enable the generation of functional components is presented in a platform agnostic manner. The methodology enables the democratisation of design by spanning both virtual and physical domains and leveraging the respective affordances of each, which, is in itself novel. This proven approach can be re-deployed in other environments as an exhaustive explanation of its requirements and functionality are presented in Chapter 6, along with the necessary steps that need to be followed to generate a capability profile in Chapter 8.

In addition to this, via means of specific deployments of the methodology in Chapter nine, a toolset and means of applying the hybrid virtual-physical methodology is presented. Rhino 6's parametric design add-on Grasshopper is shown to be a suitable environment for realising the methodology. In addition to this, the manner in which requisite models can be generated is outlined, and the incorporation of both CPs and physical testing results is demonstrated. In this way, and in a more specific and slightly meta sense, a methodology for implementing the methodology is illustrated, therefore constituting a secondary contribution to knowledge.

11.2.2 Requirements of design democratisation

Before an appropriate design methodology could be developed it was necessary to elucidate the requirements of design democratisation. This was undertaken from the perspectives of a prospective user and the capabilities of the manufacturing resource. In doing this contributions to knowledge exist in identifying:

- That decision making is a key obstacle in achieving design democratisation and that the development of intuitive interfaces is not enough to allow a novice to design functional parts. Whilst this was shown to be true for FDM, it is the author's view that this is true of any form of manufacture for functional parts.
- Significant gaps in knowledge regarding understanding of the FDM process and that designing for FDM must take this into account. The knowledge

created in filling these gaps is commented upon in the following section.

11.2.3 Creation of new knowledge of FDM process

In order to understand the requirements of the democratisation of design it was necessary to develop a thorough understanding of the FDM manufacturing process itself. This entailed a literature review and the undertaking of experimental testing to elicit additional unknown properties. These were:

- Variability of the FDM process. Test results demonstrated variation in UTS for identical test pieces.
- Identical cross sectional areas of different shapes have different UTS.
- That UTS does not scale and is linked to the ratio of solid shell and infill.

These properties were used to define the analysis approach that underpinned the functional models and permitted the requirements of a capability profile to be elucidated.

11.2.4 FDM capability profile

The development of predictive models for additive manufacture had been attempted before in existing literature but had not been implemented in the design of actual components. As such, this constitutes a contribution to knowledge as the use of an experimentally derived CP to underpin the design of functional components is novel. This work at present has not been published but a paper is currently in preparation.

In addition to this, the way in which the CP was incorporated was novel as it is used earlier in design process (ie before part geometries are defined) than with CPs in traditional subtractive manufacturing processes.

11.2.5 Publications

The aforementioned contributions to knowledge are evidenced in the following publications that were completed during the author's doctoral research.

- Journal:
  1. M. Goudswaard, B. Hicks, and A. Nassehi, ***"Towards a generalised capability profile for FDM to enable the democratisation of design,"*** Int. J. Agil. Syst. Manag., 2019 - in press.
- Conference
  1. M. Goudswaard, A. Nassehi, and B. Hicks, ***"Towards the democratisation of design : the implementation of metaheuristic search strategies to enable the auto-assignment of manufacturing parameters for FDM,"*** in Proceedings of the International Conference on Flexible Automation and Intelligent Manufacturing, 2019.
  2. M. Goudswaard, H. Forbes, L. Kent, C. Snider, and B. Hicks, ***"Different approaches to democratise design - are they equal?,"*** in Proceedings of the International Conference on Engineering Design, 2019.
  3. M. Goudswaard, B. Hicks, and A. Nassehi, ***"Democratising the design of 3D printed functional components through a hybrid virtual-physical design methodology,"*** Procedia CIRP, vol. 78, pp. 394–399, 2018.
  4. M. Goudswaard, B. Hicks, and A. Nassehi, "***Towards the democratisation of design : exploration of variability in the process of filament deposition modelling in desktop additive manufacture,"*** in Proceedings of the Conference on Transdisciplnary Engineering, 2018.
  5. M. Goudswaard, B. Hicks, J. Gopsill, and A. Nassehi, ***"Democratisation of design for functional objects manufactured by fused deposition modelling (FDM): lessons from the design of three everyday artefacts,"*** in Proceedings of the International Conference on Engineering Design, 2017.
  6. M. Goudswaard, B. Hicks, A. Nassehi, and D. Mathias, ***"Realisation of self-replicating production resources through tight coupling of manufacturing technologies,"*** in Proceedings of the International Conference on Engineering Design, 2017.

Chapter 12

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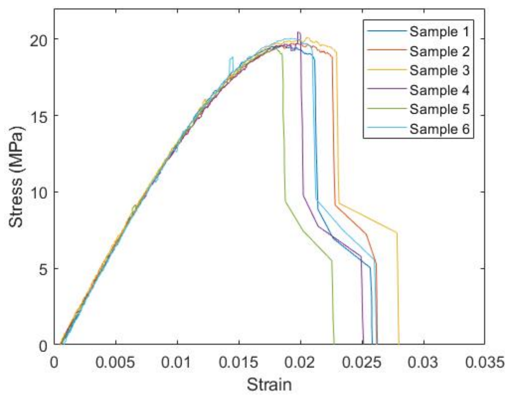
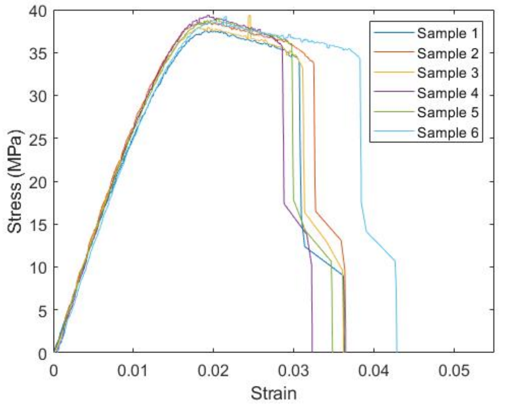
Chapter 13

Appendices

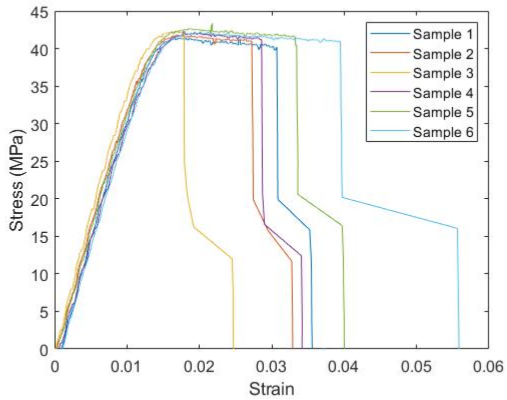
13.1 Appendix A - Stress-strain graphs from CP profiling



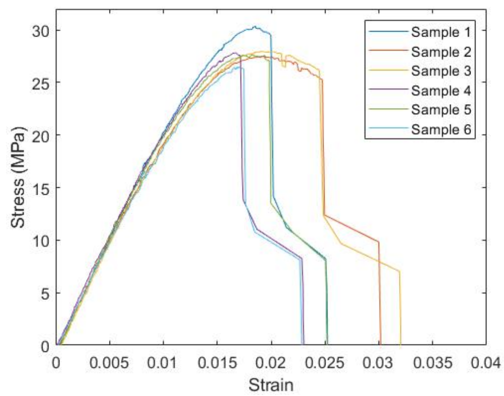
(a) *Parameter set 1*



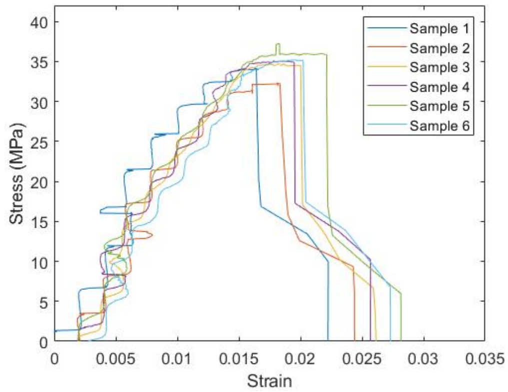
(b) *Parameter set 2*



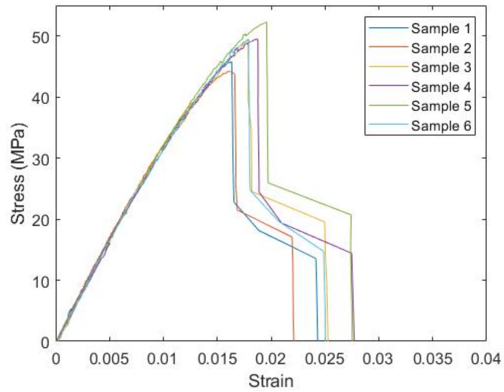
(c) *Parameter set 3*



(d) *Parameter set 4*

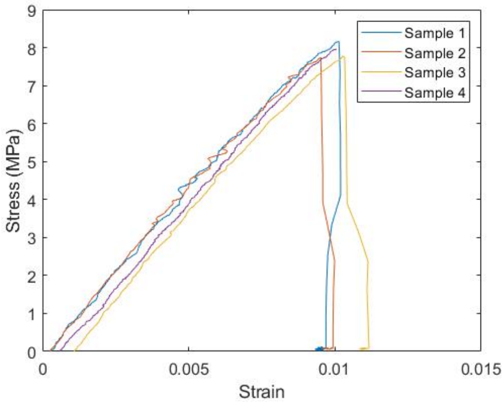


(e) *Parameter set 5*

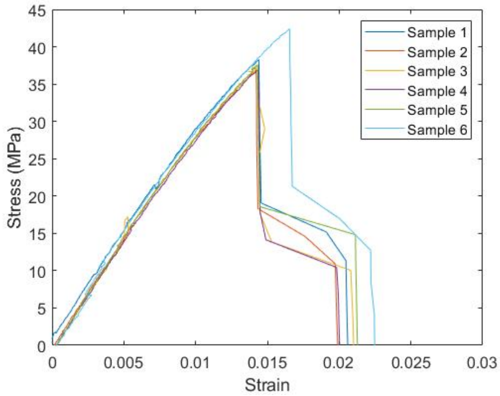


(f) *Parameter set 6*

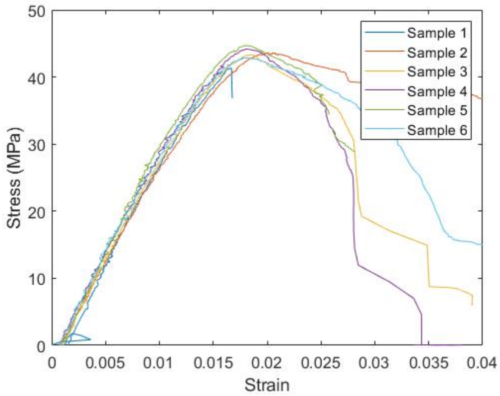
Figure 13.1 *Stress Strain Graphs for tensile tests 1-6*



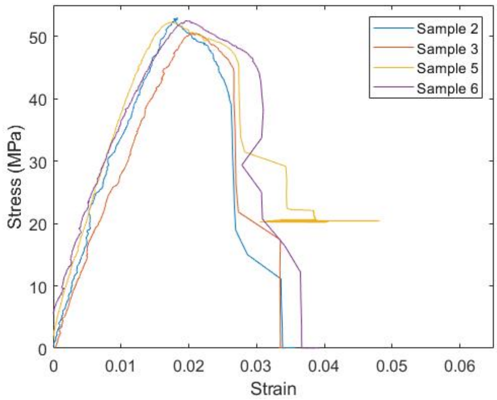
(a) *Parameter set 7*



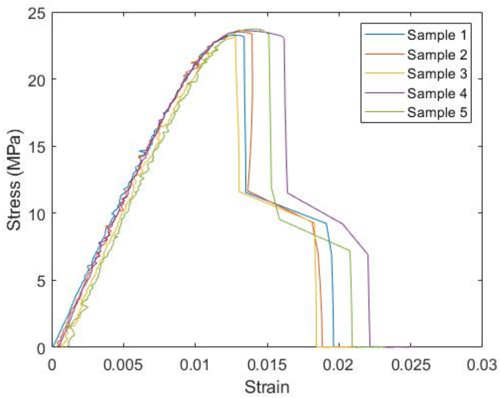
(b) *Parameter set 8*



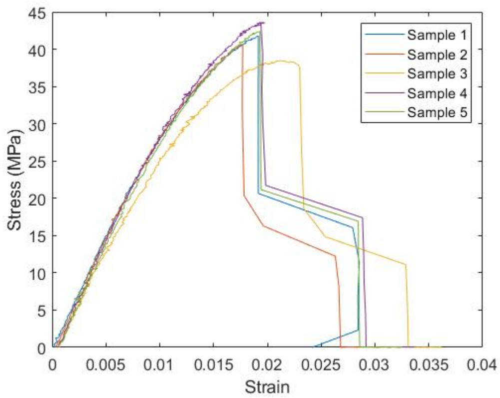
(c) *Parameter set 9*



(d) *Parameter set 10*

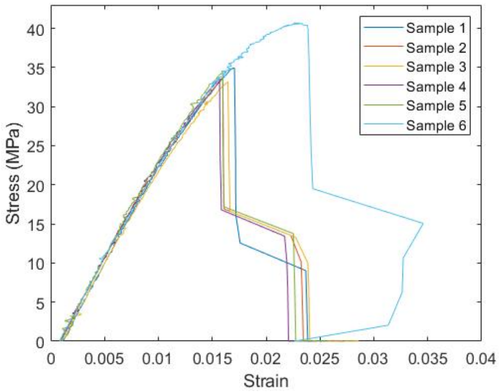


(e) *Parameter set 11*

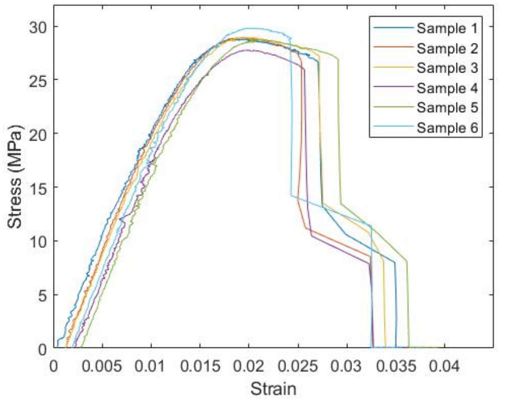


(f) *Parameter set 12*

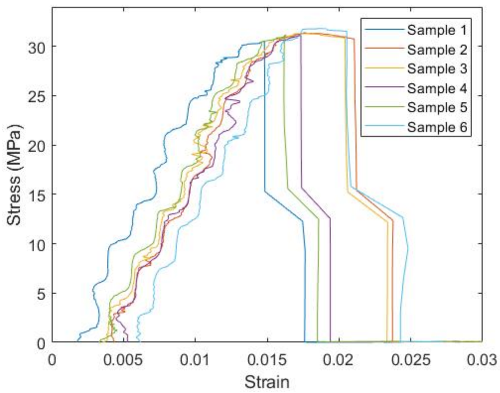
Figure 13.2 *Stress Strain Graphs for tensile tests 7- 12*



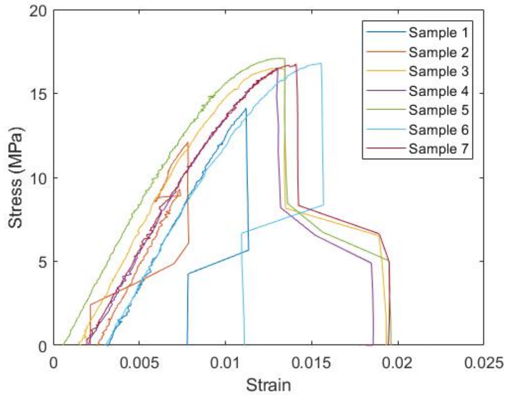
(a) *Parameter set 13*



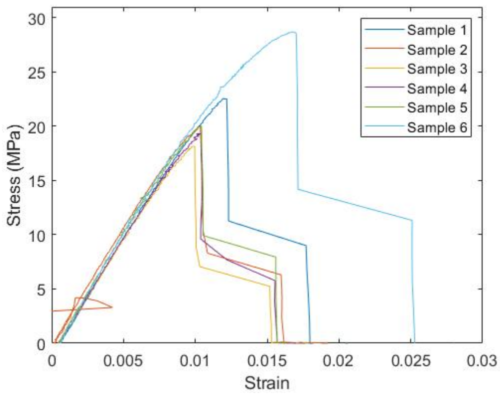
(b) *Parameter set 14*



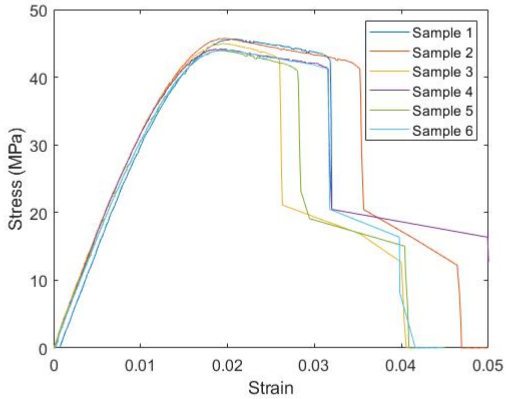
(c) *Parameter set 15*



(d) *Parameter set 16*



(e) *Parameter set 17*



(f) *Parameter set 18*

Figure 13.3 *Stress Strain Graphs for tensile tests 13 - 18*

13.2 Appendix B

13.2.1 Capability Profile Code

```
### VALUES FROM XML OUTPUT IN SPSS. THESE NORMALISE THE INPUT VARIABLES

# Layer_Height

LH_orig1=0.1
LH_norm1=-1.19207546343424
LH_orig2=0.3
LH_norm2=1.34108489636352

# Infil_Percentage

Infill_orig1=20
Infill_norm1=-1.18671032067853

Infill_orig2=100
Infill_norm2=1.15231292007915

# TB_Layers"
TB_orig1= 0.6
TB_norm1= -1.25501154243513
TB_orig2= 1.8
TB_norm2= 1.37085876173684

# Solid_Shells
SS_orig1= 0.4
SS_norm1= -1.14740854674806
SS_orig2= 2
SS_norm2= 1.21694845867218


# Elastic_Modulus

EM_orig1= 0.902459308
EM_norm1= -1.60699237949532
EM_orig2= 6.519946373
EM_norm2= 3.07511233755146
```

```
# UTS
UTS_orig1=7.706845114
UTS_norm1= -1.51940271441527
UTS_orig2= 101.6974939
UTS_norm2= 3.247271073905
# create normalisation multipliers based upon values from XML file

LH_multiplier = (LH_norm2 - LH_norm1) / (LH_orig2 - LH_orig1)
Infill_multiplier = (Infill_norm2 - Infill_norm1) / (Infill_orig2 -
    Infill_orig1)
TB_multiplier = (TB_norm2 - TB_norm1) / (TB_orig2 - TB_orig1)
SS_multiplier = (SS_norm2 - SS_norm1) / (SS_orig2 - SS_orig1)
EM_multiplier = (EM_norm2 - EM_norm1) / (EM_orig2 - EM_orig1)
UTS_multiplier = (UTS_norm2 - UTS_norm1) / (UTS_orig2 - UTS_orig1)

# create intercept values for the graphs created

LH_intercept = LH_norm1 - (LH_multiplier*LH_orig1)
Infill_intercept = Infill_norm1 - (Infill_multiplier*Infill_orig1)
TB_intercept = TB_norm1 - (TB_multiplier*TB_orig1)
SS_intercept = SS_norm1 - (SS_multiplier*SS_orig1)
EM_intercept = EM_norm1 - (EM_multiplier*EM_orig1)
UTS_intercept = UTS_norm1 - (UTS_multiplier*UTS_orig1)

# convert orientation input into three input variables for NN

if x == 1:
    BO1 = 1
    BO2 = 0
    BO3 = 0

elif x == 2:
    BO1 = 0
    BO2 = 1
    BO3 = 0

elif x == 3:
    BO1 = 0
    BO2 = 0
    BO3 = 1
```

```
# refactor continuous inputs

#receive grasshopper inputs
bias = 1
LH = u
Infill = v
TB = w
SS = s

#Normalisation ratios from SPSS XML output

LH_normXML = (u * LH_multiplier) + LH_intercept
Infill_normXML = (v * Infill_multiplier) + Infill_intercept
TB_normXML = (w * TB_multiplier) + TB_intercept
SS_normXML = (s * SS_multiplier) + SS_intercept


import rhinoscriptsyntax as rs
import scriptcontext
np = scriptcontext.sticky['numpy']

#Generate array corrseponding to input nodes of NN

a_normXML = np.array([bias, BO1, BO2, BO3, LH_normXML, Infill_normXML,
   TB_normXML, SS_normXML])

#First part of NN output array synapse weights

b = np.array([[ 1.62832936480829, 0.668062791950916, -1.70003401788377,
   1.83103059420642, 1.54291194413939, 0.255952628030032,
   0.166365405847235],
[0.0619085001971224, -0.0310979435984794, -0.739666230133224,
   0.757628758792201, 2.02979865396491, -0.13220375275757,
   0.202693108572807],
[0.979346382124381, 0.663086970169905, -0.993666431022168,
   0.217981053550411, 0.366266740515128, 0.154663340201003,
   -0.245804680130504],
[0.257418844522175, 1.31656219124526, -1.05231567475647,
   1.12773345280993, -0.555517211948211,
   -0.481293449373208,0.1977576932914360],
[-0.799129019649634, -0.157321854133181, -1.24807158884175,
```

```
   1.18852931946622, 1.86469425288263, -0.491816159409941,
   -0.192781152886156],
[2.63266832829469, 0.209582424113788, -0.059610086347341,
   0.658413035591838, -0.902603625521766, 0.505454458006752,
   0.140800921752732],
[-0.496795635830732, 2.24546718026557, 0.861283962971808,
   1.00856146747713, -2.31428948489748, 0.30602187215455,
   -0.0629008344888512],
[0.617802945560943, 1.23884238350249, 0.705650870387094,
   -0.709119735665991, -0.847181854691519, 0.249892664900599,
   -0.190074704853965]])

# c is an array of values corresponding to the hidden nodes

c_XML =a_normXML.dot(b)

c_tanh =np.tanh(c_XML)

d = np.array([bias])

# append bias calue to the beginning of hidden nodes


e_tanh = np.append(d, c_tanh)


#values for weights of synapses from hidden layer to ouput

o1 = ([[0.18804751864342],
[0.784158321792571],
[0.943748255856808],
[0.993191783421443],
[-1.27769469932538],
[1.38706456479927],
[0.40220094177377],
[-0.0262515957754911]])

o2 = ([[0.115137640840635],
[1.22361754588832],
[1.17386991366345],
[1.3166971059476],
```

```
[-1.20515739966857],
[1.34330936700613],
[-0.494039928788394],
[0.154880107514177]])

UTS_tanh = e_tanh.dot(o1)

# Un-normalise UTS output

UTS_outtanh = (UTS_tanh - UTS_intercept) / UTS_multiplier



b = UTS_outtanh
```

13.2.2 Fitness Function Code

```
import scriptcontext
np = scriptcontext.sticky['numpy']
import rhinoscriptsyntax as rs


Material_Usage = x
Targetload = z
Actualload = xx
Actualload2 = xu
Actualload3 = xv
Infill = u
Load = y[0]
height = s
width = v
TB = w
TBnumber = xz
SS = t
UTS = xy
LH = TB / TBnumber
Layers = width / LH

LoadRatio1 = Targetload / Actualload if Actualload > 0 else 1
```

```
LoadRatio2 = Targetload / Actualload2 if Actualload2 > 0 else 1
LoadRatio3 = Targetload / Actualload3 if Actualload3 > 0 else 1

LoadRatio = LoadRatio1*LoadRatio2*LoadRatio3

Overshoot = Load - Targetload

Requiredload = LoadRatio * Targetload


print UTS
print w

c1 = (0.1 if (UTS > 60) else 1) #if predicted UTS it out of bounds of CP
c2 = (0.1 if (TB > 2) else 1) #if number of TB layers is above bounds of
     CP
c3 = (0.1 if (SS > 2) else 1) #If number of solid shells is above bounds
     of CP
c4 = (0.1 if (TB < 0.5) else 1) #if number of TB layers is below bounds
    of CP
c5 = (0.1 if ((2*SS)>height) else 1) # if solid shells exceed part
    height
c6 = (0.1 if ((2*TB)>width) else 1) # if TB layers exceed part width
c7 = (0.01 if (Load<Requiredload) else 1) #encouragement penalty if load
     requirement is not met
c8 = (0.1 if (Infill<=20) else 1) # if infill percentage is too low to
    permit good print

Fitness = c1*c2*c3*c4*c5*c6*c7*c8*( min(Load,Requiredload) / (
    Material_Usage*Layers))


b = float(Fitness)
```

13.2.3 Force equations

13.2.3.1 Bending

```
# redefine variables

UTS = xy
```

```
Infill = xx

Area_infill = u
Area_shell = v
Area_total = Area_infill + Area_shell

IxxShell = y[0]
IxxInfill = z[0]
IxxTotal = IxxShell + (IxxInfill*(Infill/100))

IyyShell = y[1]
IyyInfill = z[1]
IyyTotal = IyyShell + (IyyInfill*(Infill/100))


width = xw
SS = xv
bigrad = xz

# calculate tensile force a

a = UTS * Area_total

# calculate distance moment acts

Mdist = bigrad

# calculate max bending force

y  = width/2

MaxBendingLoadX = (IxxTotal * UTS)/(Mdist*y)

MaxBendingLoadY = (IyyTotal * UTS)/(Mdist*y)

a = MaxBendingLoadX
```

13.2.3.2 Tension

```
UTS = u
E = v

Area_infill = z
Area_shell = y
Area_total = Area_infill + Area_shell

Max_load = UTS * Area_total

a = Max_load
```

13.2.3.3 Compression

```
import rhinoscriptsyntax as rs

UTS = u
E = v
radius = w
Leg_Area = 3.142 * radius * radius

Area_infill = z
Area_shell = y
Area_total = Area_infill + Area_shell

Contact_Area = min(Leg_Area, Area_total)

Max_load = UTS * Contact_Area

a = Max_load
```